Developing a numeric groundwater model to capture the interactions of the Selwyn River/Waikirikiri and local groundwater.

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By

Daniel Clark

Waterways Centre for Freshwater Management

University of Canterbury

Christchurch, New Zealand

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Abstract

In recent years summer flows in the lower Selwyn River/Waikirikiri have dropped to very low levels and this has led to questions being raised about what is causing these low flows. When the Selwyn River at Coes Ford dried in February 2017, this was the first time that the lower Selwyn had not maintained permanent flow at this location since records began at the site in 1984. This dry period generated wide public interest in the river flows and the impacts of both climate and abstraction.

As directly measuring the independent effects of climate and abstraction on flow was not possible in the Selwyn Catchment, a desktop study using existing data was undertaken. This study utilised conceptual understandings, analytical methods, and numeric modelling to better understand the drivers of low flows. As summer flows in the lower Selwyn River are spring-fed, the interactions between surface water and groundwater were a key component which needed to be captured in this study. To do this, a MODFLOW groundwater model was developed to simulate changes in groundwater levels and surface water flows. While model development and testing were the main area of focus, this was complemented by trend analysis carried out for rainfall and flow measurement sites within the study area.

The GMS interface was used to implement the MODFLOW code, using a five-layer model and a uniform 1 km grid. Model parameters were adjusted to calibrate observed steady state (average) groundwater levels and lowland stream flows. Once calibrated, the model was used to test changes in recharge and abstraction. This indicated that both could influence groundwater levels, river flows and the extent of the dry reaches in the Selwyn and Irwell Rivers. By converting from a steady state to transient model, the daily changes in longitudinal flows were able to be simulated.

Trend analysis was caried out using the Mann-Kendall test, which indicated that flows in the summer months (December- April) in the lower Selwyn River are showing significant declining

trends. These declines are not observed in the upper Selwyn River, the other surrounding rivers, or in rainfall within the study area. While the trend analysis alone does not fully explain the causes of the declining flows, it does rule out rainfall within the catchment and inflows from the hills as being the drivers of the decreasing flows.

The converging lines of evidence from the trend analysis and numeric modelling suggest that the changes in recharge drive the year-to-year variability but that the effects of abstraction are the likely cause of the longer-term declining trends. This means that the year-to-year variability is overlaid on a long-term declining trend. In more recent dry seasons, the flows in the lower Selwyn River are lower than the flows which would have occurred in historic dry seasons with lower levels of abstraction. Scenario testing also indicated that the decline in flows and extent of dry reaches could worsen if abstractors used a greater portion of their authorised volumes.

Acknowledgements

This thesis is the product of a journey learning about groundwater modelling and how to undertake academic research. There are many people who have assisted me throughout the course of this research and this thesis could not have been completed without their help. I would like to take this opportunity to thank those people and organisations who helped make this research happen.

Firstly, my lead supervisor Leanne Morgan who has provided guidance, advice, and review comments to help me stay on track and focused. Without Leanne's advice this project could have easily kept expanding into unending model reworking and refining. I also wish to acknowledge my supporting supervisory panel members, Tim Davie from Environment Canterbury and Julian Weir from Aqualinc Research Limited, for helping to guide the direction of this study. I particularly acknowledge the benefit gained by receiving Julian's advice on technical questions relating to the implementation of MODFLOW using the GMS interface; this saved me a lot of trial and error.

I wish to thank Environment Canterbury for supporting me through this thesis and for providing the required equipment and software licenses. And thanks to my colleagues in the hydrology and groundwater teams who assisted with accessing data and were always happy to answer my questions. Particular thanks go to Wilco Terink and Mike Kittridge who helped with extracting some of the very large data sets required for my modelling; without their database skills a very long manual process would have been required to access these data.

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1. Introduction

As rivers flow across gravel plains, they can interact with the surrounding groundwater system, which can lead to surface flow being lost or gained. There are many examples of these surface water-groundwater interactions occurring within Canterbury, with the Selwyn River/Waikirikiri being a case study where research has highlighted observed changes in flows over time (Mckerchar & Schmidt, 2007). The areas around the Selwyn River have been subject to large scale development over recent decades and groundwater allocation has provided a reliable source of irrigation water. In the 2016- 2017 dry period, the Selwyn River was observed to go dry at the lower catchment flow monitoring location at Coes Ford for the first time since records began in 1984. This dry period and the public response to this, highlighted the need to better understand the drivers of flow in the lower Selwyn River, specifically the role of climate and abstraction on summer low flows.

This research investigates the interactions between surface water and groundwater in the Selwyn/Te Waihora Catchment. The specific focus area for the research is the drying reaches of the Selwyn River, and capturing these within the numeric groundwater model MODFLOW. As this catchment has been studied extensively, this research uses a desktop approach by using existing field data for analysis and modelling. The catchment scale modelling provides tools to test different climate and abstraction scenarios in a simplified way and assists with understanding the causes of extremely low flows in dry summers.

1.1 Research aim and objectives

Aim

This research aims to simulate surface water-groundwater interaction between the Selwyn River and adjacent aquifer systems using a numeric groundwater modelling code.

Objectives

1. Develop a conceptual model of the interactions between the Selwyn River and local groundwater.
2. Develop a numeric model of the surface water and groundwater systems of the Selwyn River.
3. Develop the ability to simulate the effects of changing groundwater level on surface water in the Selwyn River.
4. Simulate time series of flows for key locations on the Selwyn River.
5. Use the developed numerical model to simulate the spatial extent of the drying reaches of the Selwyn River under different climatic and abstraction situations.

Study implications

- Enhance understanding of the ability to model surface water-groundwater interactions on a catchment scale.
- Enhance understanding of the local consequences of groundwater management on surface water flows.
- To develop a tool which allows investigation into the implications that changes in groundwater may have on the surface water flows in the Selwyn River.

2 Background

2.1 Surface water-groundwater interaction

Surface water bodies interact with surrounding groundwater; this occurs through surface water being lost to groundwater, groundwater discharging to the surface water body, or both in combination (Khan & Khan, 2019; Winter, 1999). These interactions are considered to be important for the management of both the surface water and groundwater systems (Woessner, 2000). The interactions can occur across differing scales, from regional surface water-groundwater exchange (Barthel & Banzhaf, 2016), to sub-reach interactions within the hyporheic zone (Harvey & Wagner, 2000).

Surface water-groundwater interaction occurs both naturally and because of human activities. Water abstracted from groundwater can impact on flows and water levels of nearby water bodies. As water is pumped from a well, the local groundwater level is reduced (drawdown). This drawdown can influence surface water-groundwater interaction by intercepting water which would otherwise discharge into the surface water or by inducing losses from water already in the surface water body. The water that is abstracted from the groundwater system is initially sourced from the reduction in aquifer storage; as pumping continues the flows and water levels of nearby waterbodies can be reduced (Theis, 1940). The increased recharge from streams to groundwater and the reductions in discharge to streams from groundwater because of groundwater pumping is referred to as ‘stream depletion’.

Barlow & Leake (2012) describe the two key factors that influence stream depletion as the separation distance between the abstraction point and the stream, and the hydraulic diffusivity of the surrounding aquifer. Simply put, the smaller the separation and the higher the hydraulic conductivity of the aquifer, the greater the connection between the well and the stream.

The effects of stream depletion may be observed in flow records of surface water bodies; this could be a reduction of flow that corresponds with the groundwater pumping. However, stream depletion effects may take time to develop and the interactions between climate, natural variations in flow and groundwater, and other wells being pumped, may make it difficult to isolate the impact of each well.

Figure 2.1 provides a conceptual diagram of the effect of pumping from a well on a nearby waterbody. The water pumped from the well *Q* [L^3/T] causes a drawdown effect in the groundwater system and ultimately reduces the water level or flow in the nearby waterbody.

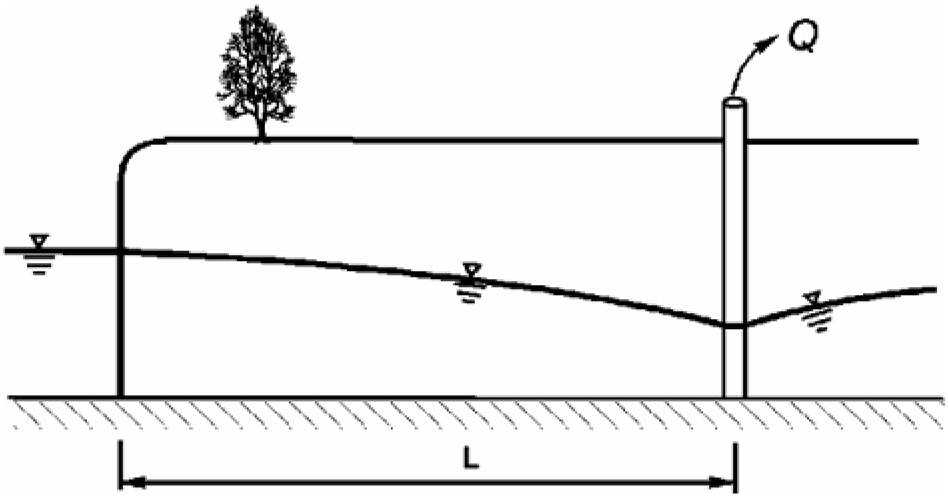

Figure 2.1 Conceptual diagram of a stream depleting groundwater take in an unconfined aquifer (from Hunt, 1999)

Stream depletion effects can be estimated with simple analytical methods, such as those defined by Theis (1935), Hunt (2003) and Hunt & Scott (2005). These solutions allow the user to calculate the impact a well will have with a nearby stream based on the separation distance *L* [L] (see Figure 2.1), the pumping rate *Q*, and the properties of the aquifer being pumped from and the connected stream.

Each groundwater abstraction can be assessed for its stream depletion component, but this approach would not easily capture the cumulative impacts of many widely distributed abstractions. To quantify the cumulative effects of many distributed abstractions requires a spatially distributed model which can simulate the combined effect of many small reductions in groundwater.

Managing the immediate stream depletion effects and the long-term cumulative effects requires a combination of approaches. Surface water and shallow groundwater takes that are deemed to have an immediate stream depletion effect on the river can be restricted at times of low flow in the river. However, abstractions which are deeper or more distant from the river may not be able to be managed using flow-based restrictions due to the timing of effects in the waterway not being immediate; this means that the benefit of ceasing abstraction may not be seen until after the time of low flow has passed. When the effects of abstraction leads to a drop in groundwater level, the discharges from the groundwater level also drops, resulting in spring-fed streams declining (de Graaf et al., 2019; Zipper et al., 2018, 2019). de Graaf et al. (2019) highlight the global value of groundwater abstraction for irrigation and food production, but also report that the impacts of this abstraction will reduce stream flows much before shortages of groundwater are experienced.

2.1.1 Surface water/groundwater investigations

Studies investigating surface water-groundwater interaction have been carried out both locally within New Zealand, and in many other countries around the word. These studies can generally be grouped into field-based studies, with local examples discussed here, and modelling studies, which are discussed in the next section.

Surface water-groundwater interaction can be investigated using a range of methods. Field based methods include concurrent flow measurement, water chemistry, groundwater piezometric surveys and tracer studies (Coluccio, 2018). Modelling studies can also provide understanding of surface water-groundwater interactions. Modelling-based studies can be of use when the researcher is investigating ‘scenarios’ rather than observed conditions. Often surface water-groundwater researchers use both modelling and field-based studies. Combining both approaches provides locally-specific input and calibration data, while allowing testing of conditions not observed in the field.

Research carried out on the Ashburton River by Coluccio (2018) investigated differing methods of quantifying flow between surface water and groundwater in a hill-fed braided river. The field-based study concluded that multi-method approaches are beneficial for capturing surface water-groundwater interactions as they can capture a range of spatial and temporal conditions.

Investigation into the surface water of the Orari River in South Canterbury used an extensive field study with numeric groundwater modelling to describe the surface water and groundwater systems, and the interactions (Burbery & Ritson, 2010).This investigation included a multi-year field study measuring surface water flows, surrounding groundwater levels and chemistry combined with modelling.

On the Selwyn River there were a series of field campaigns and modelling studies which investigated different parts of surface water-groundwater interactions and the implications for instream ecosystems (Datry & Larned, 2008; Larned et al., 2011; Larned et al., 2010; Rupp et al., 2008; Snelder et al., 2013). Similarities between the Orari and Selwyn Rivers were also investigated through the work of Larned et al. (2011). This research developed a modelling approach which correlated flows along a losing and gaining braided river with permanent flow recorder sites at the top and bottom of the catchment. The work of Larned et al. (2011) included the two examples in Canterbury and also included a braided river in France.

The complexity and spatial scale of surface water-groundwater interaction means that it is often impractical to capture all aspects with field measurements. Modelling provides an opportunity to build on field observations, to help develop a fuller understanding, or to test what may happen under alternate conditions to those which have been observed.

2.2 Modelling of surface water and groundwater

Modelling surface water and groundwater has often been done independently of each other, with many software packages or models focusing on one or other phase in the water cycle. As computing power has increased, models have been able to become more complex and able to solve complex non-linear equations over large spatial areas within manageable timeframes. Many groundwater studies have been completed using the finite difference model MODFLOW developed by the U.S Geological Survey (Harbaugh, 2005). While MODFLOW was originally focused on modelling groundwater flows, it has been coupled with surface water models such as the Soil & Water Assessment Tool (SWAT) to simulate surface water and groundwater within a catchment (Sophocleous & Perkins, 2000). The development of surface water modules within MODFLOW enabled users to capture surface water and groundwater within a single model. The different modules have different levels of surface water-groundwater interaction. The River Package, Stream Flow Routing Package (SFR) and Stream Flow Routing Package 2 (SFR2) include the ability for surface water bodies to lose or gain flows from the groundwater system (Niswonger & Prudic, 2010; Prudic et al., 2004). The SFR2 Package uses a simplification of the one-dimensional Richards equation (Richards, 1931) to approximate vertical flow through a homogeneous unsaturated zone, and can be the most detailed way of capturing surface water-groundwater interaction within MODFLOW.

Other models take similar approaches, but with different ways to solve the same problem. The 3D finite element groundwater models FEMWATER and FEFLOW can also be used for modelling changes in groundwater levels and discharges, but do not have the same routing and loss and gains of the SFR2 Package. However, these models have been used for catchment applications including in Selwyn/Te Waihora (Weir, 2005, 2007) and can be coupled to surface water routing models. The development of MIKE SHE was intended to create an integrated surface water and groundwater model (Butts & Graham, 2005). This model has a similar groundwater component to MODFLOW and uses the Richards equation to simulate flow through an unsaturated zone.

Within New Zealand, surface water and groundwater have been successfully modelled in many areas such as Marlborough and Hawkes Bay, both of which have areas like the Canterbury Plains. In Canterbury there have been numerous modelling studies on catchments where surface water and groundwater interact. In South Canterbury, studies by Burbery & Ritson (2010), Durney & Dodson (2019) and Durney et al. (2019) captured flows and shallow groundwater; they also predicted flows at specific reaches of the rivers to simulate flows impacted by groundwater level changes.

In Hawkes Bay, Rakowski et al. (2018) used MODFLOW with the SFR Package to simulate the impacts of many groundwater takes on surface water flows. This modelling showed the cumulative impacts of many takes, which individually would be considered to have minor effects on surface water flows. This situation is like that seen in the Selwyn/Te Waihora Catchment.

In Marlborough, studies on the Wairau River simulated surface water-groundwater interaction on a braided river (White et al., 2016; Wöhling et al., 2018). The work of White et al. (2016) used 3D terrain and lithology models to estimate static groundwater pressure, whereas the work of Wöhling et al. (2018) used a MODFLOW model to simulate the exchanges between surface water and groundwater in a similar way to this thesis.

There have been numerous local modelling studies investigating surface water, groundwater and their interactions within the Canterbury Plains, and the modelling used in these is described in section 2.3.3 of this thesis.

2.3 Selwyn River/Waikirikiri background

There have been extensive studies and monitoring of the Selwyn River and surrounding groundwater system. This includes many years of monitoring by Environment Canterbury and the National Institute of Water and Atmosphere (NIWA); both organisations have long term monitoring sites within the catchment and have made these data available for use. There have also been studies by the University of Canterbury and Lincoln University, and many research organisations.

This research builds on the existing work in the catchment and uses the extensive existing field data for the Selwyn/Te Waihora Catchment and a desktop modelling approach to assist with the understanding of surface water-groundwater interaction.

2.3.1 Catchment description

The Selwyn River/Waikirikiri Catchment extends from the foothills of the Big Ben Range to its discharge point into Te Waihora/ Lake Ellesmere. The Selwyn River is classified as a hill-fed braided river and exchanges water with the groundwater system as it crosses the Canterbury Plains. The Canterbury Plains are a wide expansive plains area, which has been formed by the deposition of gravels by the major alpine rivers.

The Selwyn River is fed by the North and South Branches of the Selwyn River and it emerges from the foothills near the township of Whitecliffs. As the Selwyn River crosses the plains it joins with its three major tributaries, the Hawkins, Waianiwaniwa and Hororata Rivers. Often these tributaries are dry on the surface at their respective confluences, as they lose flow to groundwater as they cross the gravel plains. Near the confluences of these tributaries with the Selwyn River mainstem there is often a gain in flow even if the tributary is not contributing surface flow (Clark, 2011, 2014; Vincent, 2005). The upper reaches of the Selwyn River are permanently flowing where the river leaves the hills and is also permanently flowing where it discharges to Te Waihora. Surface flow is intermittent through much of the mid-reaches of the river. In the upper plains the Selwyn River is perched above an unconfined aquifer (Larned et al., 2008; Vincent, 2005); in the lower plains there are a series of formations which result in the coastal confined and semi-confined aquifers. In the lower plains, groundwater levels are near the surface and in places artesian.

At times of high flow from the foothills, the Selwyn River can flow for its entire length, but at lower flow the mid-reaches are dry. At the coastal end of the Selwyn Catchment sits Te Waihora, a large shallow coastal lake. The catchment of Te Waihora includes the Selwyn River and a large number of other spring-fed streams which emerge on the lower plains. These are fed by the surrounding groundwater system.

The Selwyn River provides the largest volume of water to Te Waihora, but as it is hill-fed, its flows are much more variable than the spring-fed inputs to the lake. Over the summer months the Selwyn River often experiences times of low flow and at these times the spring-fed streams provide a large portion of the inflow to Te Waihora. As the Selwyn River and Te Waihora both interact with the same groundwater resource, this research focuses on the wider Selwyn/Te Waihora Catchment, including the many spring-fed streams which discharge into Te Waihora.

There is a large body of work that has been completed which investigated flow issues in the Selwyn River Catchment, particularly investigating the connectedness of the Selwyn River as it crosses the plains to Te Waihora. A number of these studies looked at correlations between surface water flows at different points down the Selwyn River and predicted where losses and gains were occurring down the river profile (Clark, 2011; Rupp et al., 2008). Regional modelling studies of the Canterbury Plains have also included the Selwyn River and catchment but were predominantly focussed on groundwater and the discharge from groundwater in the lower river. These regional groundwater studies did not prioritise the simulation of river dynamics as the Selwyn River crossed the plains (Hunt, 1975; Scott & Weir, 2014; Thorley & Scott, 2010; Weir, 2005, 2007).

2.3.1.1 Hydrology

As the Selwyn River is a hill-fed braided river, its surface flow is a result of the combined hydrogeology, geomorphology and climatic conditions which can vary temporally and spatially throughout the catchment (Rupp et al., 2008; Trush et al., 2000). The natural complexity can be added to by the effects of water abstraction within the catchment.

The Selwyn River has had a flow monitoring station at the top of the plains at Whitecliffs since the 1960s and a second station at the bottom of the catchment at Coes Ford since the early 1980s. Having continual monitoring at the top and bottom of the plains has allowed comparisons of flows and allows conclusions to be drawn on the influence of groundwater abstraction on flow.

The Selwyn River Catchment covers a large area of foothills but only a narrow slice of the plains area, which is shown in Figure 2.2. Much of the mid-plains area has no natural surface waterways and lower pains are dominated by modified spring-fed waterways. The wider Te Waihora Catchment captures a much larger area, and this reflects the contribution of groundwater to stream flows and to the lake.

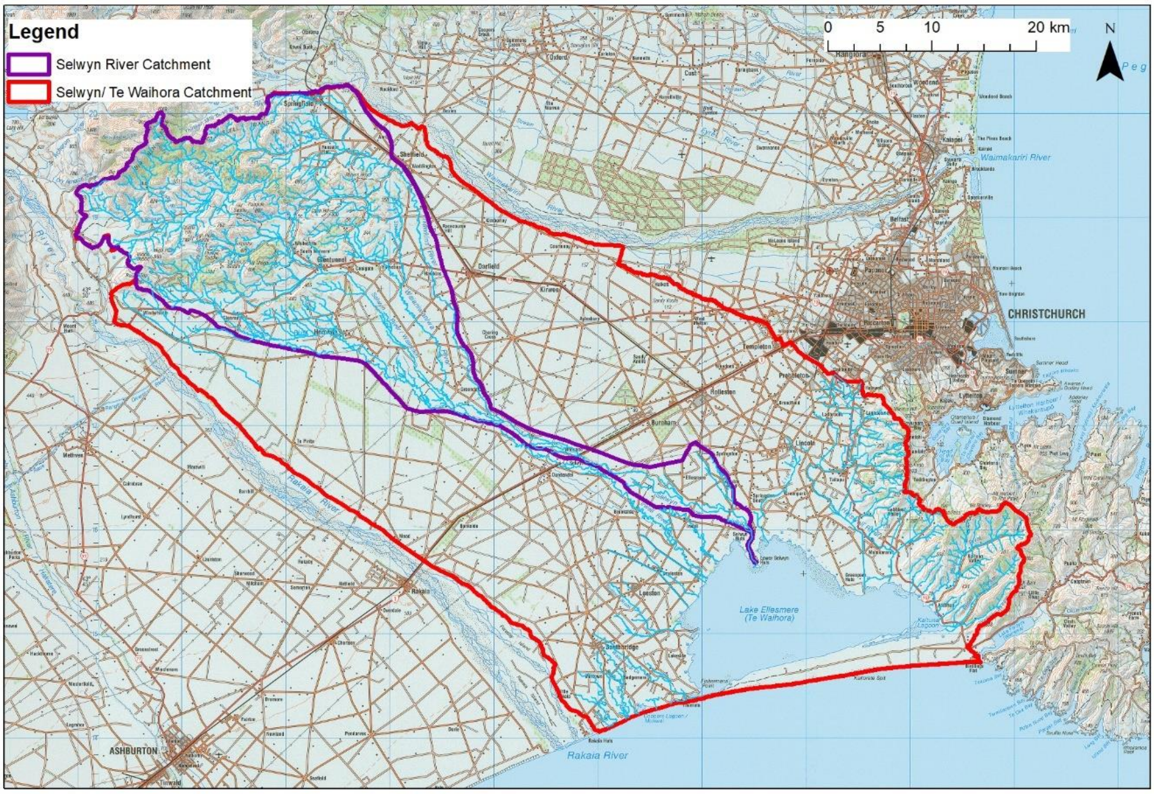

Figure 2.2 The Selwyn River and Te Waihora Catchments and waterbodies within these.

The Selwyn River has complex hydrological properties, with perennial losing and gaining reaches, permanent flow at the top and bottom of the catchment, and a dry reach which persists for much of the year (Larned et al., 2008). This complexity led to a long term study commencing in 2003 which yielded a range of research describing the catchment and simulating flows down the length of the river (Larned et al., 2008, 2011; Larned, Arscott, et al., 2010; Mckerchar & Schmidt, 2007; Rupp et al., 2008). These papers highlighted the influence of surface water-groundwater interaction and the impacts of abstraction but were generally focused on the surface water flows.

In their study, Mckerchar & Schmidt (2007) highlight the complexity of conclusively identifying the cause of reduced flows in the lower Selwyn River, due to the lack of water use data when they completed their study, and also as the low flows have coincided with lower than normal recharge. They described the flow in the lower Selwyn River as showing a greater decreasing trend than can be attributed to flow from the upper catchment and recharge occurring on the plains. They also noted that the decrease is consistent with the increased abstractive pressures that have occurred in the catchment with the increased uptake of irrigation. The Mckerchar & Schmidt (2007) study focused on comparing time series flow data from permanent monitoring sites in the upper and lower Selwyn River. These time series data allowed conclusions to be drawn on the possible cause but did not provide an ability to test their conclusion by simulating different levels of abstraction.

Data from NIWA and Environment Canterbury monitoring stations can be used to assess trends in flows within the Selwyn River. The 7-day annual low flow is a metric used to describe the seven lowest consecutive days' flow. Comparing the 7-day annual low flows recorded at Whitecliffs and Coes Ford shows a trend in the Coes Ford flow but not in the Whitecliffs flow (Figure 2.3). This analysis aligns with that of Mckerchar & Schmidt (2007), who completed a similar analysis but looked at the 90-day annual low flows, which represent an overall summer flow. Both analyses highlight that the changes in flow at Coes Ford cannot be explained by changes occurring in the foothills (Whitecliffs). This trend in flow has occurred over a period when abstractive pressures have been increasing.

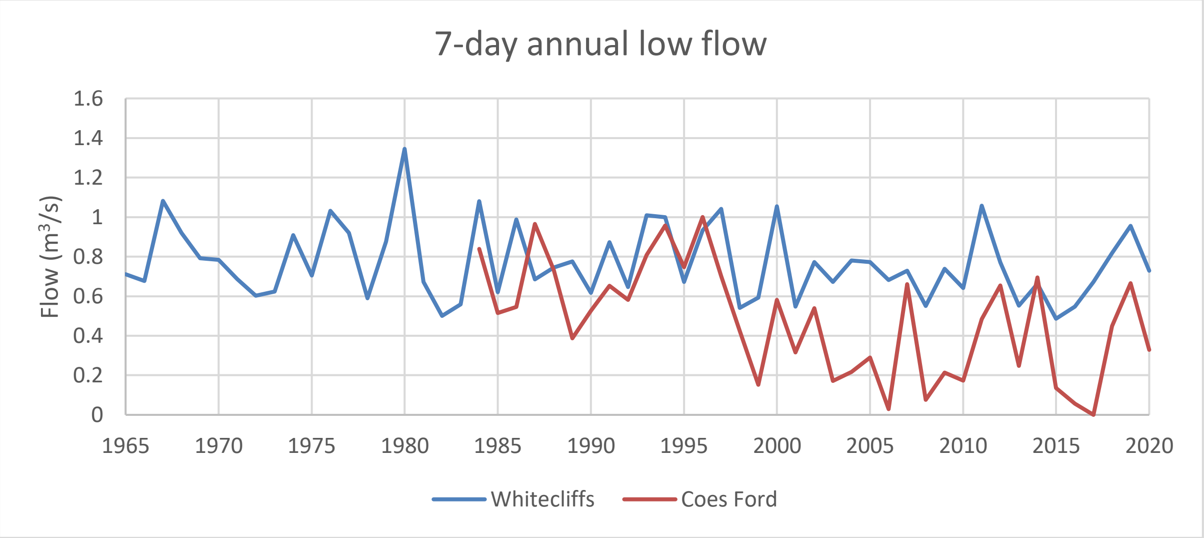

Figure 2.3 Annual 7-day low flows in the Selwyn River at Whitecliffs and Coes Ford (data sourced from Environment Canterbury and NIWA).

Springs are not common in the upper plains of the Selwyn Catchment, and those that exist are located close to rivers, particularly between the Hororata River and Selwyn River. Springs in the upper plains are likely to be fed by shallow subsurface flow from the Selwyn River and its tributaries, rather than from deeper aquifers (Vincent, 2005). This agrees with Vincent's conceptual model of a shallow unconfined aquifer surrounding the Selwyn River and its tributaries. In the lower plains, springs are common and are likely to be fed from aquifers which reflect the wider catchment's groundwater conditions.

Around the shore of Te Waihora are many spring-fed streams. These streams have much more stable flows than the Selwyn River and do not experience the same magnitude of high flows, nor is there as much variation in flows across the seasons. As these spring-fed streams occur on low topographic gradient areas, they do not have clearly defined catchment boundaries and are fed by water that recharges groundwater some distance away from the streams. The L-II and Halswell Rivers are large spring-fed rivers located to the east of the Selwyn River and both have high baseflow relative to mean flow, highlighting the stable nature and influence of groundwater inflows.

To both the north and south of the Selwyn/Te Waihora Catchment there are areas of high spring flows, related to the neighbouring alpine river losses. In the north the Waimakariri River loses flow and large spring-fed flows emerge in the Otukaikino, Avon, Styx, and Heathcote Rivers. A similar area is seen to the south of the catchment where the losses from the Rakaia River provide stable spring flows to the Lee River, Tent Burn and Jollies Brook, this area is known as the Little Rakaia zone.

2.3.1.2 Geology and hydrogeology

Groundwater resources in the upper plains can be found in three aquifers - 0-30m, 40-85m and greater than 100m below ground level, with the top two aquifers having extents which are situated around the Selwyn River and tributaries; these are unconfined and semiconfined

(Vincent, 2005). These aquifers are considered to have significant leakage occurring between them. The dominant source of recharge for the top two aquifers is from the Selwyn and Hororata Rivers and this is confirmed by water levels and groundwater chemistry (Vincent, 2005).

In the lower catchment there are a series of confined and semi-confined coastal aquifers. These have been formed by glacial and interglacial periods resulting in deposition of fine materials on what would have been coastal areas at times of higher sea level. The fine materials which make up the aquitards have been deposited during interglacial periods and the gravel aquifer material has been deposited during glacial periods. The fine materials can be considered as aquitards and form the confining layers for the coastal aquifers under Christchurch City and the lower Selwyn/Te Waihora Catchment.

The majority of the Selwyn/Te Waihora Catchment consists of alluvial gravels deposited across the fans of the Waimakariri and Rakaia Rivers. Between these two major fans the Selwyn River has also deposited alluvial gravels (Anderson, 1994).

A geological model has been developed of the eastern parts of the Canterbury Plains (Begg et al., 2015) which provides information on the depths and spatial extent of the major geological formations. A layer of the base of the quaternary sediments has been derived by Jongens (2011), which can be considered to be the bottom of the aquifers of interest in this research. Using a combination of the conceptualisation of geology by Begg et al. (2015), Vincent (2005) and Jongens (2011) provides coverage of the majority of the Selwyn/Te Waihora Catchment.

Table 2.1 outlines the geological formations found in the coastal areas of the Canterbury Plains that make up the aquifer and aquitard layers (Begg et al., 2015). The horizontal hydraulic conductivities in Table 2.1 have been estimated based on the materials in each layer using the published values for each material in Freeze & Cherry (1979).

Table 2.1 Geological formations in the lower plains, including estimates of material and horizontal hydraulic conductivity (Kh)

Geological formation	Aquifer/ aquitard	Material	Upper Kh (m/d)	Lower Kh (m/d)
Springston	Aquifer	Gravel, sand, silt	86400	86.4
Christchurch	Aquifer	Gravel, sand, silt	86400	86.4
Avonside	Aquitard	Clay	8.64E-05	8.64E-08
Riccarton	Aquifer	Gravel, sand, silt	86400	86.4
Bromley	Aquitard	Clay	8.64E-05	8.64E-08
Linwood	Aquifer	Gravel, sand, silt	86400	86.4
Heathcote	Aquitard	Clay	8.64E-05	8.64E-08
Burwood	Aquifer	Gravel, sand, silt	86400	86.4
Shirley	Aquitard	Clay	8.64E-05	8.64E-08
Wainoni	Aquifer	Gravel, sand, silt	86400	86.4
Base of Quaternary	Basement	Rock	0.000864	8.64E-08

2.3.1.3 Te Waihora

Te Waihora/Lake Ellesmere sits at the bottom of the Selwyn Catchment and can be considered the receiving environment for water and land management up stream. Te Waihora is a large shallow lake which has no permanent outlet. The lake level has been managed by generations of Māori and European settlers by manually creating a channel through the beach barrier (Horrell, 1992). These manual openings are to keep the lake level low enough to protect low-lying land from flooding. The levels at which Te Waihora can be opened is set out in the National Water Conservation (Te Waihora/Lake Ellesmere) Order 1990 and were amended via a change to the Order in 2011.

The lake receives freshwater from the Selwyn River and surrounding spring-fed lowland streams. There is also some seepage of groundwater through the lakebed. The seepage from groundwater is estimated to be approximately 440L/s based on seepage tests (Ettema & Moore, 1995). Due to the low gradient of the streams, the lake level influences the water level in the lower reaches of the streams which flow into Te Waihora. The wetland margins of the lake can also become inundated when the lake level is high.

2.3.1.4 Drainage and water race networks

Within the Selwyn/Te Waihora Catchment there has been widespread drainage works and construction of water races to provide stock water supplies across the plains. These works have been extensive and cover much of the catchment.

The Selwyn District Council (SDC) operates three stock water schemes across their district: the Ellesmere, Malvern and Paparua schemes. These stock water schemes provide water sourced from the Rakaia, Waimakariri, Kowai and Selwyn Rivers across the plains in a series of race networks. These race networks date back to the 1880s and were originally constructed by early settlers (Taylor, 1996). The water races have now formed part of the catchment landscape and contribute recharge to the groundwater system. The water races lose a large portion of their flow and only a small amount of the water that enters the races is used by stock. Field investigation indicates that approximately 80-90% of the water in the races is lost to groundwater. Figure 2.4 shows the stock water race network currently operated by SDC.

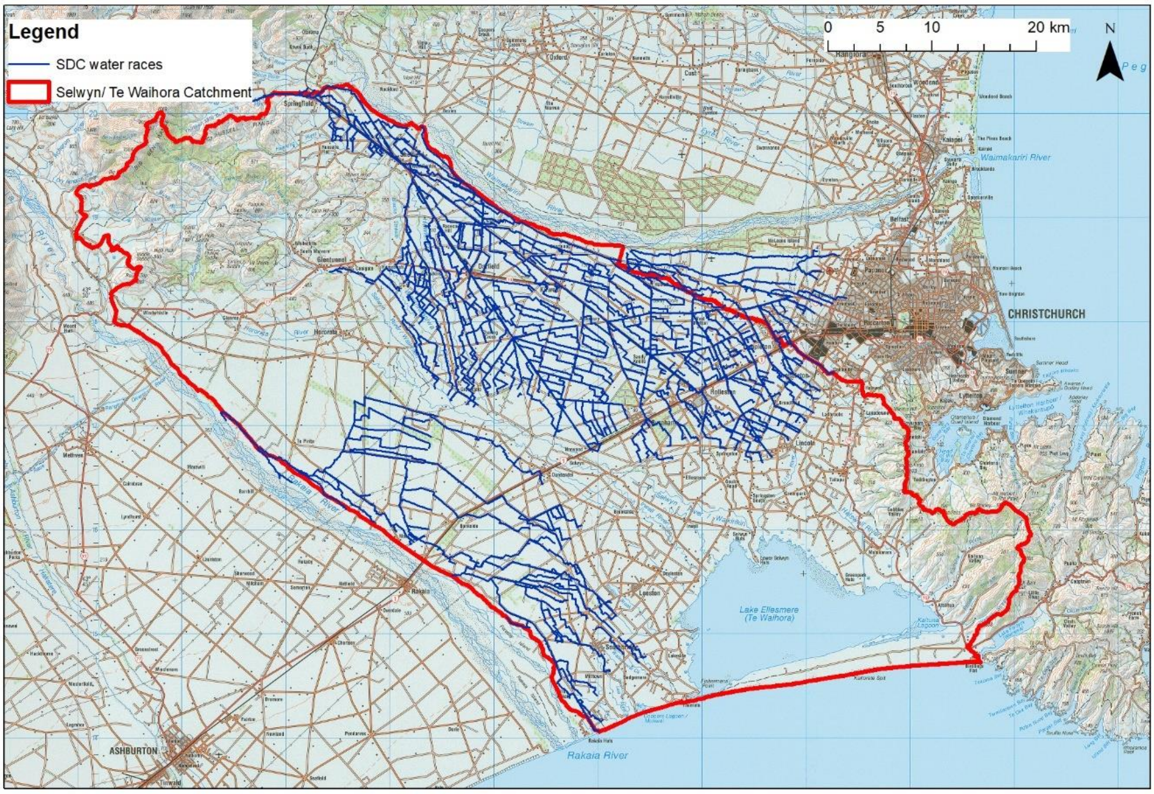

Figure 2.4 Stock water race network operated by Selwyn District Council.

Without the drainage interventions that have occurred, much of the eastern parts of the catchment would have poor drainage or be subject to flooding (Taylor, 1996). The lake level management combined with drainage networks across the lower plains has allowed extensive land development. Many of the spring-fed lowland streams around Te Waihora have been straightened and channelised to improve land drainage. This has led to the perception that these only exist for drainage purposes, however they are modified natural water courses which provide instream values (Golder Associates, 2012). Figure 2.5 shows the extent of the drainage network surrounding Te Waihora. The management responsibility for this is split between the regional and district councils.

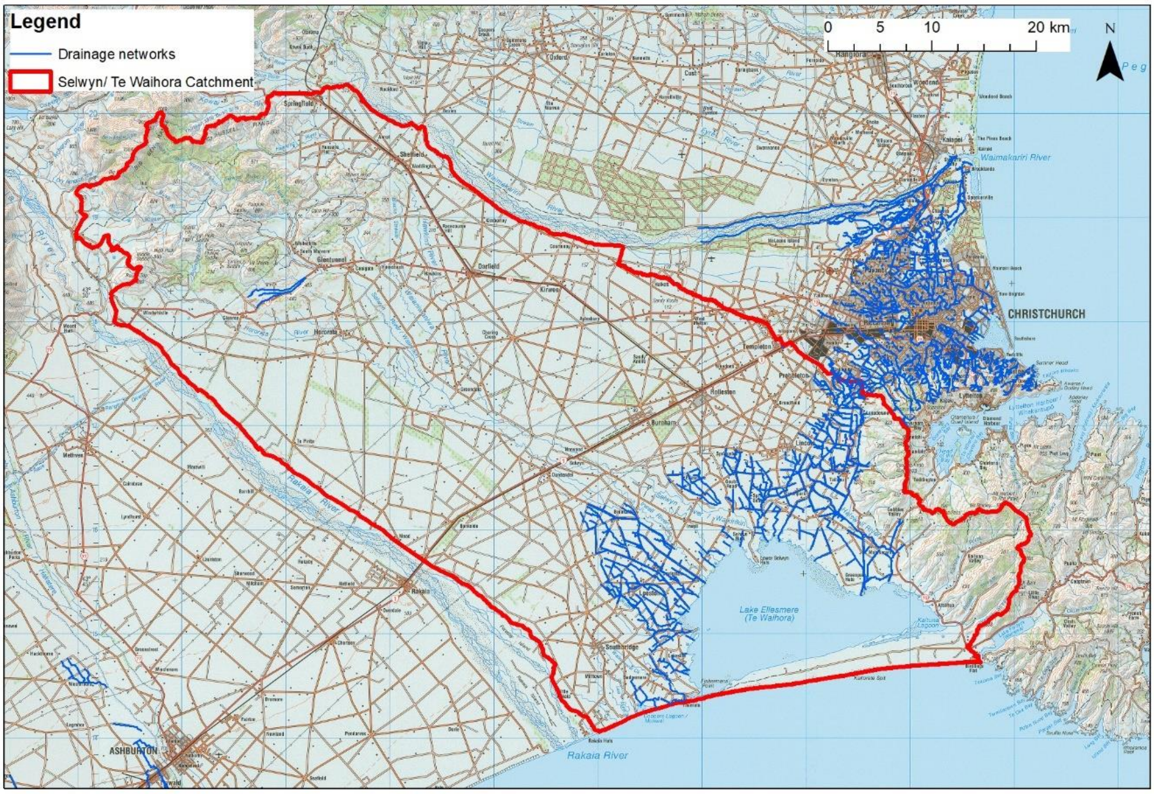

Figure 2.5 Drainage networks in the Selwyn/Te Waihora Catchment and surrounds

2.3.2 History of water management

2.3.2.1 Water allocation in the catchment

In the Selwyn and Te Waihora Catchment there has been a long history of farming and water abstraction. The Selwyn River marks the boundary of two water allocation zones in the catchment, the Rakaia-Selwyn allocation zone to the South and the Selwyn-Waimakariri zone to the north. These two water allocation zones are areas where the regional council has set annual volume limits on water abstraction. Within the Selwyn/Te Waihora Catchment, most of the abstraction is from the groundwater system and is not restricted at times of low flow. To manage the cumulative effects of groundwater abstraction on surface water, allocation needs to be set at a level which ensures an acceptable reduction in spring-fed flows (Clark, 2014).

Demand for water has increased over recent decades in the Selwyn/Te Waihora Catchment; most of this abstraction has been from groundwater. Figure 2.6 shows the surface water and groundwater allocations consented in each year. These show a rapid increase over the 1990s and early 2000s and a plateau in recent years. This is due to the allocation limits for the catchment being met, and in many places overallocated, which means access to further allocation is limited.

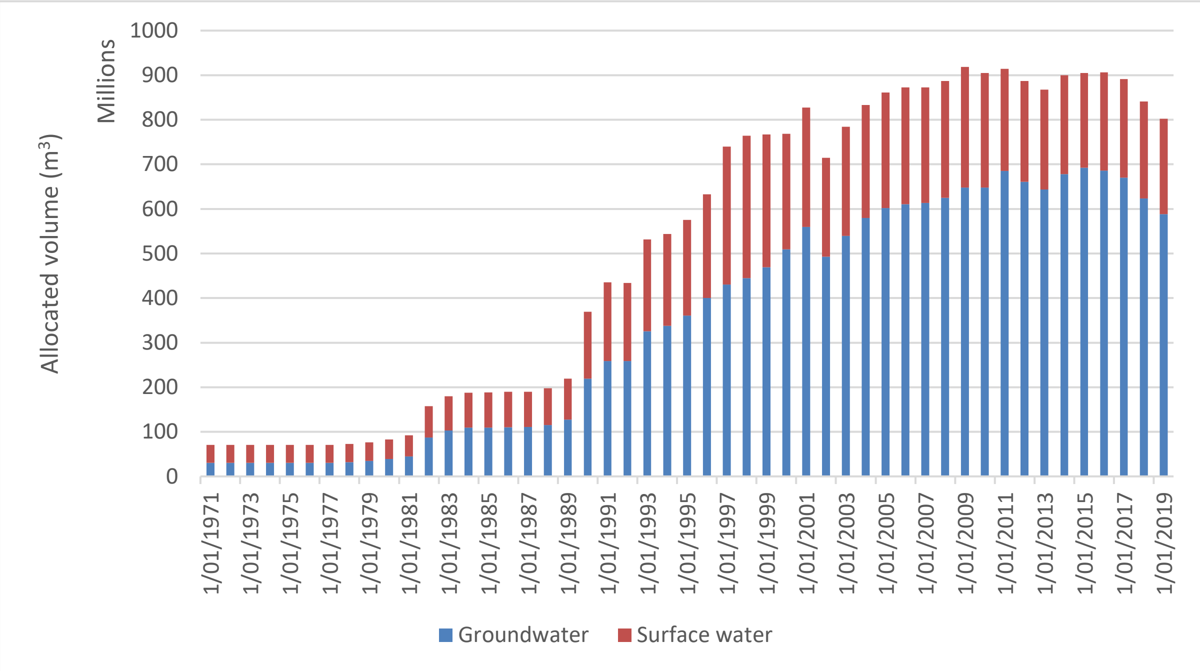

Figure 2.6 Water allocation over time within the study area

The distribution of groundwater takes in the Canterbury plains is shown in Figure 2.7. These abstractions occur from both unconfined and confined aquifers. Abstractions occur at a wide range of depths; for example, deep wells near Christchurch City are used to access safe drinking water supplies, and shallow wells are used for irrigation near Te Waihora where the groundwater level is near the surface.

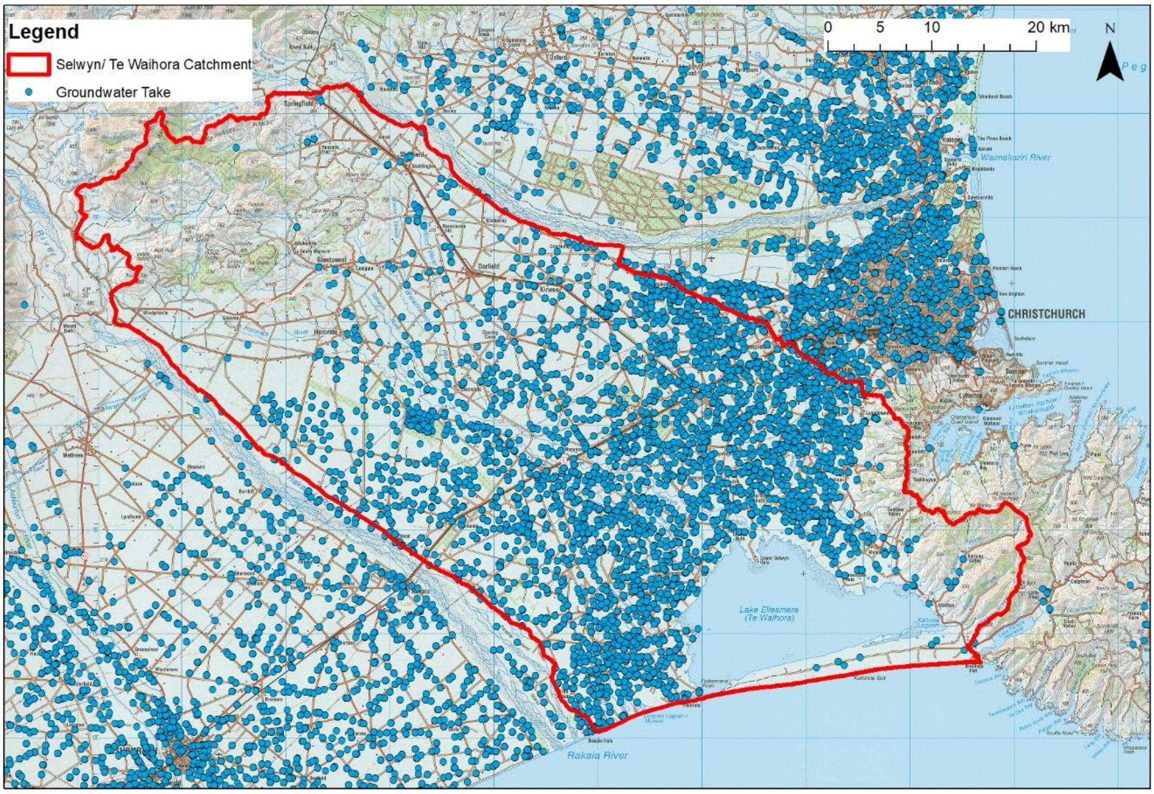

Figure 2.7 Groundwater abstraction points within the Selwyn/Te Waihora Catchment and wider Canterbury Plains

When groundwater is allocated to an abstractor in Canterbury, the abstraction must be shown to not impact on neighbouring properties' existing abilities to abstract water, or to cause stream depletion in nearby waterways. If pumping from the well is deemed to be stream depleting from a nearby waterway the abstraction may be restricted at times of low flow in the waterway. These restrictions impact on the abstractor's ability to use water when they need it. These rules have incentivised abstraction of deeper groundwater that is not considered to be stream depleting and is therefore unrestricted at times of low flow. The many deep, non-stream depleting groundwater takes in the Selwyn/Te Waihora Catchment can be considered to be influencing the regional water level rather than immediately affecting streams; this is resulting in a longer-term cumulative effect on streams fed by the groundwater system (Clark, 2011; Scott & Weir, 2014; Williams et al., 2008).

Under previous planning frameworks it was possible to be granted further allocation in an overallocated catchment. If the applicant argued a case that their abstraction was not worsening the impacts on the environment, they may have been granted their consent through a hearing. A landmark case was Lynton Dairies vs Canterbury Regional Council, where the applicants took the regional council to the environment court and won the right to double their irrigation in the over-allocated Rakaia-Selwyn zone (*Lynton Dairy v Canterbury Regional Council NZ Resource Management Act decision C108/2005*, 2005). This case highlighted the risk of individual applicants being granted water in overallocated catchments due to the inability to prove their additional abstraction would be the cause of negative environmental impacts.

Driven by the demand for further development in the Selwyn/Te Waihora Catchment, the Central Plains Water (CPW) irrigation scheme was proposed to bring water from an alpine water source into the catchment. Bringing additional water into the catchment would allow further irrigation areas to be developed and could be used to replace irrigation which was being abstracted from the groundwater. The scheme consents were granted in July 2012. The scheme can supply surface water from the Rakaia and Waimakariri Rivers to up to 60,000ha of irrigated land in the upper plains of the Selwyn/Te Waihora Catchment. The scheme has been developed in stages, with the first (stage 1) covering 23,000ha on the south side of the Selwyn River near to the confluence of the Hororata River. Stage 2 is completed and covers 20,000ha between the Selwyn and Waimakariri Rivers. The Sheffield Water Scheme is also completed and provides water to 4,100ha (*Scheme Development – Central Plains Water Limited, Christchurch, NZ*, n.d.).

In Canterbury, water is generally allocated to provide sufficient water to meet crop demands in nine years out of ten. This means that in most years abstractors do not need all the water that they have been allocated. Previous studies have suggested that average water use is approximately half of the consented allocation (Rajanayaka et al., 2009; Sanders, 1997).

Recently abstractors have been required to meter their water use, which also shows a similar pattern to the previous studies, confirming that abstractors use much less than their allocation in most years.

The declines in flows and groundwater levels that have been attributed to abstraction (Clark, 2014; Mckerchar & Schmidt, 2007; Williams, 2014) are a result of the current levels of abstraction, not the total allocated water. As there is a large quantity of water that has been allocated for use, but is not currently being used, the impacts of abstraction could potentially worsen as abstractors more fully utilise their consented allocations. This could lead to lower groundwater levels and further declines in spring-fed stream flows, including the lower Selwyn River.

As the CPW scheme is located in the upper plains, flows and groundwater levels are likely to be impacted on both sides of the Selwyn River and its tributaries, both through reduced groundwater abstraction and increased recharge to local groundwater. As this is occurring in the upper parts of the plains there is likely to be an impact on flows down the length of the river and some change in the drying reaches.

2.3.2.2 Land use and irrigation

The Canterbury Plains are host to large areas of agriculture, much of which is dependent on growing crops or pasture for animal feed. The combination of large flat areas and favourable growing conditions have led to large-scale uptake of irrigation, as water is often the limiting factor for plant growth. The uptake of irrigation drove the increases in water allocation and once allocation limits were met and it became more difficult to secure new allocation, irrigation became more efficient. Almost all the irrigation within the Selwyn/Te Waihora Catchment is spray irrigation and much of that is supplied via centre pivot irrigators. Figure 2.8 shows the distribution of irrigation across the catchment. The most extensive areas of irrigation in the catchment occur between the Selwyn and Rakaia Rivers.

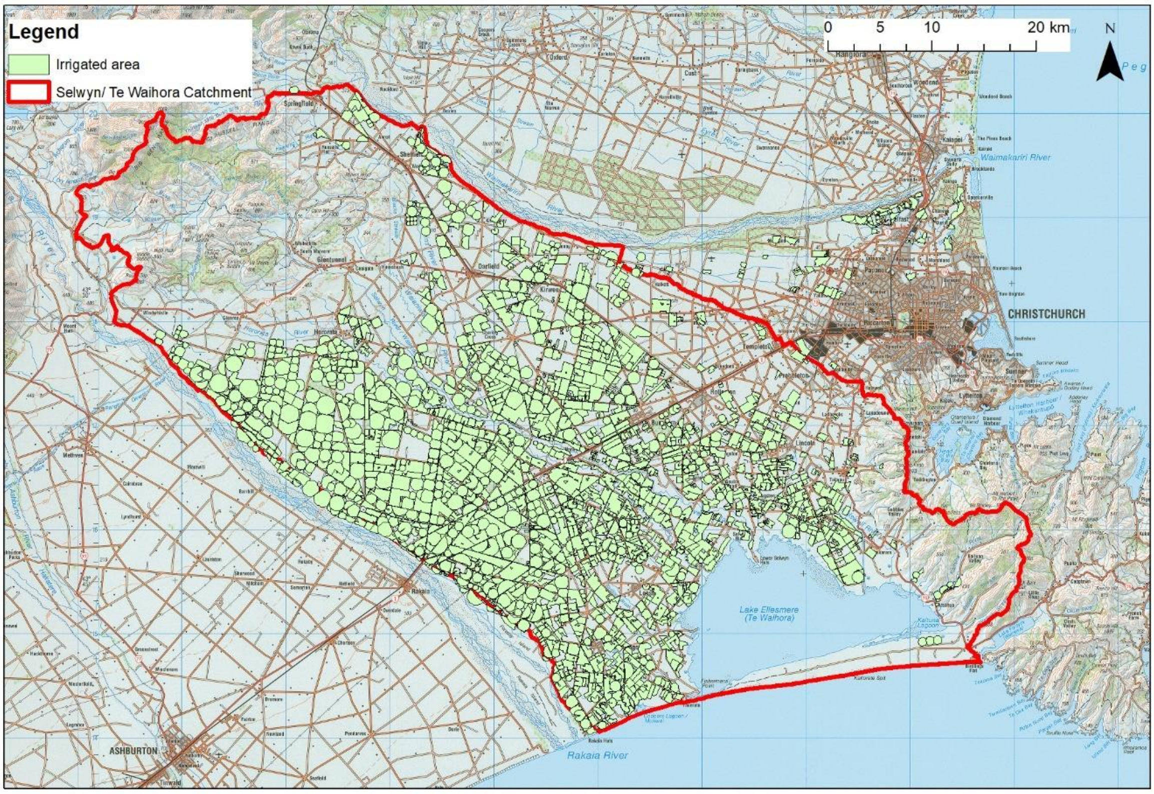

Figure 2.8 Irrigated areas mapped as green polygons, as of 2016.

Most of the irrigation water in the catchment is sourced from groundwater. However, with the development of the CPW irrigation scheme in the upper catchment, some irrigators have replaced or supplemented their groundwater supplies with water sourced from the alpine rivers. This reduces the demands placed on the groundwater resources.

Land use varies across the catchment, with large areas of sheep and beef farming, dairy farming, cropping and other farming types mixed with lifestyle blocks and urban areas. The Selwyn/Te Waihora Catchment has had a large population influx following the Canterbury Earthquakes. In this research the focus is on water quantity and flows, so the particular land use is not as important as it would be if the focus was on water quality.

2.3.3 Previous modelling studies

Within the Selwyn/Te Waihora Catchment and the surrounding Canterbury Plains there have been numerous studies completed which have involved modelling the Selwyn River and groundwater system. The focus of these has usually centred on either surface water or groundwater but seldom captured detail on both. A selection of relevant local modelling studies is summarised below.

A series of papers were produced which focused on the longitudinal changes in surface flow between the flow recorders located at Whitecliffs (in the upper catchment) and Coes Ford (in the lower catchment) (Larned et al., 2011; Larned, Arscott, et al., 2010; Rupp et al., 2008). Rupp et al. (2008) described the losses in surface flow occurring for approximately 40km downstream of the foothills, and the river becoming perennially flowing before entering Te Waihora. The flow losses can at times occur over short distances, with dry reaches occurring within 3km of the foothills (Datry et al., 2007).

The work of Larned et al. (2010, 2011) updated that of Rupp et al. (2008) and refined their model of surface water flows down the Selwyn River mainstem. The development of the Empirical Longitudinal Flow Model (ELFMOD) correlated spot gauging data at user defined intervals. This allowed prediction of flows at any location on the mainstem. A similar approach was taken in Clark (2011, 2014), but correlations were only developed at locations where spot gaugings had been carried out. These modelling methods allowed for reconstruction of historic daily flow records at many locations on the Selwyn River. A limitation of these empirical modelling methodologies is that the user is unable to estimate flows under different conditions, such as climate conditions or different abstraction pressures. They provide an insight into the spatial and temporal flow variation under historic conditions, which were not captured with traditional monitoring methods.

The eigen model approach has been used several times in the Selwyn/Te Waihora Catchment and also the wider Canterbury Plains to simulate the effects of pumping and climate on groundwater levels and spring-fed flows (Bidwell et al., 1991; Rupp et al., 2009; Williams, 2010). The eigen model approach is a lumped conceptual 1D groundwater model which can be quickly run in excel spreadsheets (Bidwell et al., 1991). This approach estimates changes to groundwater levels and flows based on levels of land surface recharge and abstraction. But, due to the lumped nature of eigen models they are unable to be used to answer complex spatially distributed modelling problems.

Thorley & Scott (2010) produced a MODFLOW model using the interface Groundwater Vistas. This model covered the Canterbury Plains and was focused on simulating the regional groundwater system. Development of this model ceased when an alternative FEMWATER model was applied for water management planning by the regional council (Scott & Weir, 2014).

The Selwyn/Te Waihora Catchment underwent a water management planning process from 2010 to 2014 which involved a large amount of research carried out by Canterbury Regional Council and other parties with interest in the outcome of the planning process. This led to the progression of several models and the loose coupling of surface water and groundwater models in an effort to simulate the changes in surface water flows as a result of groundwater pumping. As these models were focused on simulating water movement and quality over the entire Selwyn/Te Waihora Catchment, the local scale interactions within the Selwyn River were not evaluated in detail.

The Canterbury Groundwater Model (Weir, 2005, 2007) was developed using the finite difference groundwater model FEMWATER and included the Selwyn/Te Waihora Catchment. This model was updated and applied in conjunction with modelling by Clark (2014) to estimate changes in stream flows resulting from changes in groundwater levels and abstraction. The losses and gains in the Selwyn River and tributaries were quantified by Clark (2011, 2014) and estimates were made based on the changes in the groundwater model described by Scott & Weir (2014).

As a response to the modelling by Clark (2014) and Scott & Weir (2014), Cetin (2015) coupled a FEMWATER model based on Weir (2007) to E-source to simulate changes in discharge in groundwater dependant streams. While these models were simulating the same catchment using similar methodology, the conceptual model underlying the implementation differed. The Cetin (2015) model conceptualised that water in the lowland streams was not derived from the wider groundwater system and the water in those streams was sourced from very local shallow groundwater, with much of the land surface recharge water being discharged offshore.

This selection of models which have been applied in the Selwyn/Te Waihora Catchment highlight that there are many different approaches to modelling which can and have been taken in this catchment. As the previous modelling studies have used many different modelling platforms and assumptions behind the models, they have not been directly comparable to each other. Due to the complexity of the catchment one single approach has not proven to be superior for answering all questions that are raised by researchers and water resource regulators. The range of models and application of them has focused on different parts of the catchment and water balance, but none have focused on simulating the changes in flows in the Selwyn River as it crosses the plains, resulting from changes in groundwater levels and abstraction. The effects of abstraction on groundwater levels and lowland stream flows, emerging from the groundwater system, has been simulated using both analytical (Bidwell & Morgan, 2002) and numeric models (Scott & Weir, 2014; Weir, 2018). However, the abstraction occurring within the catchment is widespread and can impact on flows across the catchment, including the drying reaches of the Selwyn River. These effects have generally only been investigated on a case by case basis using analytical stream depletion calculations

(Hunt, 2003; Theis, 1940) to assess the impacts of individual abstractions on nearby river reaches.

2.4 Conceptualisation of the catchment

Based on the existing research and monitoring data, the following conceptualisation of the Selwyn/Te Waihora Catchment has been developed. A conceptual model is the starting point for developing a numeric model of the catchment as it captures the key components of the water balance for the catchment and the interactions between different water bodies; it also includes sources and sinks for water (Betancur et al., 2012). The conceptual model may be refined through the numeric model development as the modeller develops a better understanding of the catchment. The conceptual model components are described below. This conceptualisation groups the water inputs and exports from the system together and describes the movement of water within the catchment. The conceptualisation captures both water entering and exiting the catchment, and exchanges which occur within the catchment. Inputs and exports are defined in relation to the groundwater system.

2.4.1 Water inputs

Water entering the system comes from several sources and the dominant driver for the water inputs is climate. The following are the key components considered to be relevant for modelling the surface water-groundwater interaction in the Selwyn/Te Waihora Catchment:

Rainfall recharge. The portion of the rainfall which falls on the land surface, infiltrates and recharges to the groundwater system.

Inflows from the hill-fed Selwyn River and Tributaries. The upper Selwyn River and tributaries lose flow to groundwater, providing recharge.

Irrigation recharge. When land is irrigated, the water content within the soil profile is retained at a higher level than un-irrigated land. This increased soil moisture content can lead to increased recharge.

Losses from water races. The large network of water races in the Selwyn/Te Waihora Catchment provide water primarily for stock drinking; these races lose much of their flow which contributes to groundwater recharge.

Recharge from the Waimakariri and Rakaia Rivers. The alpine rivers which flow on either side of the Selwyn/Te Waihora Catchment both exhibit surface flow losses as they travel across the plains and both contribute recharge to the groundwater system.

Some recent research has highlighted that water from north of the Waimakariri may travel under the Waimakariri River into the Selwyn/Te Waihora and Christchurch City groundwater systems (Etheridge & Hanson, 2019). However, this has not been considered as part of this research due to the uncertainty around the magnitude and timing. It is expected that if water is flowing under the Waimakariri River, it is unlikely to influence the day-to-day losses and gains in the Selwyn River as it crosses the plains.

2.4.2 Water discharges

Water leaves the Selwyn/Te Waihora groundwater system via a range of different pathways; these are conceptualised as follows:

Spring-fed stream flows. Surface water in the lower parts of the Canterbury Plains is fed mostly from groundwater discharge. These stream flows are influenced by surrounding groundwater levels.

Groundwater abstraction. There are many groundwater abstractions within the catchment. These abstractions are generally unrestricted at times of low flow and are for both irrigation and other uses.

Evapotranspiration. Evapotranspiration is the combination of the two processes where water is lost from the soil surface through evaporation and also from plants through transpiration (Allen et al., 1998). This can be considered as a reduction in recharge rather than a loss from groundwater.

Evaporation also occurs from open water bodies, such as rivers and lakes. Evaporation is an important component of the water balance for Te Waihora due to it being shallow with a large surface area. As the water balance of Te Waihora is not part of this research, open water evaporation has not been included in the modelling.

Seepage into Te Waihora. Water discharges through the bed of the lake into Te Waihora. The extent of the seepage is quite uncertain but has previously been estimated as approximately 440L/s (Ettema & Moore, 1995). As there is not detailed information about the spatial or temporal distribution, this value is assumed to be the average of the seepage across the total area of lakebed.

Offshore discharge. Groundwater flow does not stop at the coast. Groundwater can discharge out into the ocean to the coast north and south of Banks Peninsula. The quantity of this discharge is uncertain and is often calculated as the remainder in a water balance. This research takes a similar approach and treats offshore discharge as the unknown remainder in the water balance.

2.4.3 Flow directions

Conceptualising how components of the water balance interact with each other is an important step that needs to be taken prior to building any model (Betancur et al., 2012). In the Selwyn/Te Waihora Catchment flow directions can be interpreted from water level monitoring and water chemistry. Water chemistry provides information on its age and source (Stewart et al., 2002; C. B. Taylor et al., 1989). As groundwater moves in three dimensions, it also needs to be conceptualised in three dimensions. Figure 2.9 shows a conceptualisation of how water moves in the horizontal plane.

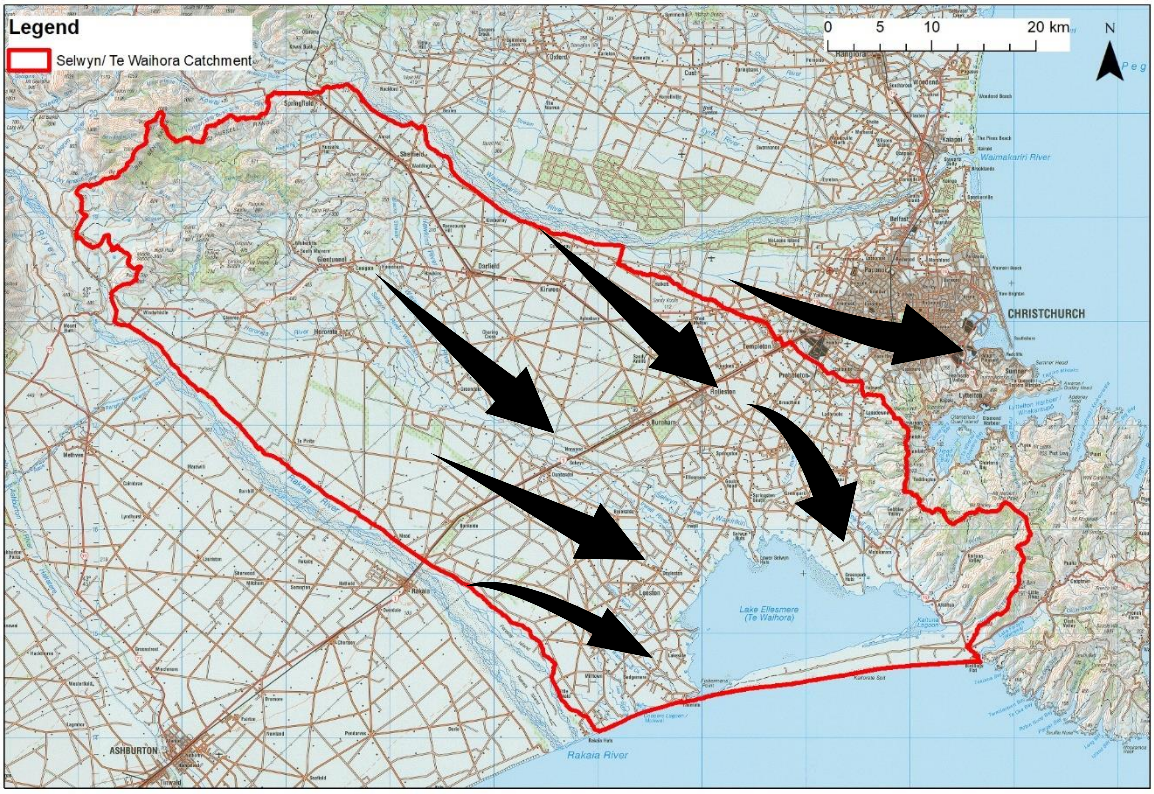

Figure 2.9 Conceptualisation of horizontal groundwater movement in the study area, based on chemistry and flow data.

Land surface recharge which occurs in the Selwyn/Te Waihora Catchment flows towards Te Waihora, as does water lost from the Waimakariri River which crosses the upper plains. In the lower plains, water lost from the Waimakariri flows towards Christchurch City, feeding the urban waterways. In the south of the catchment, losses from the Rakaia River provide water to the Little Rakaia zone and also influence the southern streams which enter Te Waihora through a pressure response. The influence of the two alpine rivers plays an important role in the flow direction in the Selwyn/Te Waihora Catchment. The low permeability volcanic material of Banks Peninsula also influences flow direction by creating a flow barrier which forces groundwater towards Christchurch City and Te Waihora.

In the vertical direction, the geological formations of the Canterbury Plains influence how water moves. Figure 2.10 shows the conceptualisation of vertical flow paths in the catchment. Water recharges through the surface in the upper plains into the unconfined aquifers and flows down the gradient towards the coast. Near the coast the confining and semi-confining layers create impediments to flow, increasing hydraulic heads in the confined aquifers. This results in high groundwater levels near Te Waihora and some areas where groundwater is artesian due to pressures in the confined and semi-confined aquifers.

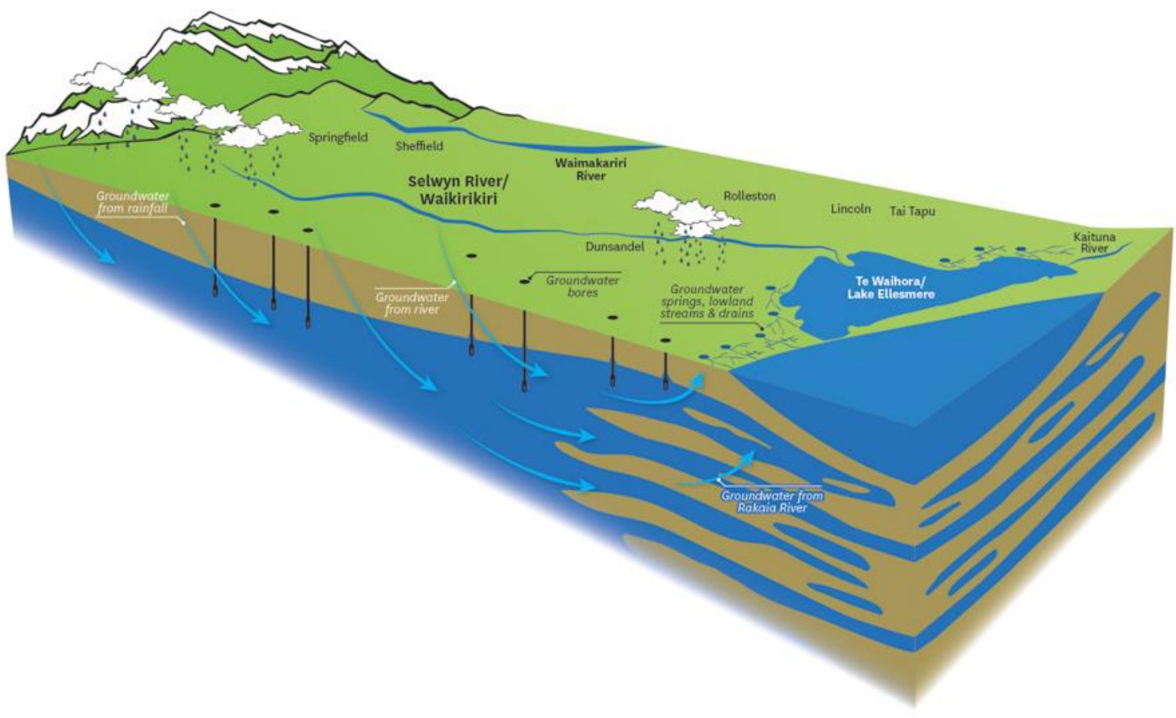

Figure 2.10 Block diagram conceptualising the vertical flow paths in the Selwyn/ Te Waihora Catchment (source Environment Canterbury (n.d))

The conceptualisation of water flows in the catchment suggests that changes in recharge or abstraction across the catchment will have an impact on flow in the lowland streams and groundwater level in the lower catchment. This conceptualisation also suggests that losses from the upper rivers is less influenced by abstraction, as the groundwater level is already far below the river levels in the upper plains.

3 Methods

3.1 Overview

Understanding the hydrology of the Selwyn River and the interactions of surface water and groundwater with differing climate and abstractive pressures poses a significant challenge. This can be addressed in different ways, ranging from in-depth long-term field monitoring to detailed computer simulation of the catchment, both of which can require large amounts of resources.

In this research, a desktop approach has been taken. This builds on existing research in the Selwyn/Te Waihora Catchment and uses data collected over a longer duration than could be collected over the course of this thesis. To understand the drivers for declining flows in the Selwyn River, two different methods have been employed, which allows a wider range of data to be included in the analysis. The two methods used in this research are trend analysis using recorded data in the catchment and a simple numeric groundwater model to simulate changes in areas and under conditions where observations may not have been historically captured. These two approaches complement each other and provide two lines of evidence to help understand the interactions between surface water and groundwater.

3.2 Trend analysis

As modelling results can be subject to considerable uncertainty, further analysis of recorded data was carried out. This analysis builds on the work of Mckerchar and Schmidt (2007) who looked at flows in the Selwyn River, and also that of Alkhaier et al. (2019). Mckerchar and Schmidt (2007) found that 90-day low flows in Selwyn River at Coes Ford were showing a significant decreasing trend over the data they analysed, whereas 90-day low flows in the Selwyn River at Whitecliffs were not showing any trend. This led them to conclude that the decreases in flow in the lower catchment could not be attributed to climate alone.

Alkhaier et al. (2019) investigated trends in recharge, groundwater levels and flows in spring-fed streams in the Canterbury Plains, including within the study area for this thesis. They found decreasing trends in many groundwater levels and stream flows. These trends were found to align with a trend of decreasing recharge over this period. The decreasing recharge over the study period was determined to be caused by climatic conditions. Alkhaier et al. (2019) found that groundwater abstraction has been increasing by 0.84 million m^3 per year since 1967. As recharge was found to be declining and abstraction was increasing, the declining groundwater levels and stream flows were consistent. The study concluded that both abstraction and climate affect flows and groundwater levels, but weather is the main driver of variability.

As the Selwyn River has characteristics of both a hill-fed river and a lowland spring-fed river, it is possible for some parts of the flow hydrograph to be changing over time while other parts may not have any trend or possibly show opposite trends at different flows or times of the year. To test for trends, the tool Time Trends (version 6.4) was used to evaluate flow time series data. A Mann-Kendall test (Helsel & Hirsch, 2002; Kendall, 1948; Mann, 1945) was used to test for trends in recorded data. This test provided p values to show statistical significance, and also Sen Slope, which indicates the magnitude and direction of change (Sen, 1968).

The variables which were tested for trends in recorded data, were flow, rainfall and potential evapotranspiration. Data for these sites were extracted from Environment Canterbury and NIWA's climate database. Trend analysis is normally carried out on data which spans many years, but not all sites in the study area have long term records, particularly flows in lowland streams. A minimum record length threshold was used to determine which sites could be included in this analysis. Table 3.1 shows the data used at each site included in this trend analysis.

Table 3.1 Sites and parameters included in trend analysis.

Site	Parameters evaluated	Date range
Selwyn River at Coes Ford	Annual mean flow, monthly mean flow, 7-day ALF	1984-2019
Selwyn River at Whitecliffs	Annual mean flow, monthly mean flow, 7-day ALF, monthly rainfall, annual rainfall	1963-2019 (flow) 1984-2019 (flow) 1988-2019 (rainfall)
Waimakariri River at Old Highway Bridge	Monthly mean flow	1967-2019
Rakaia River at Fighting Hill	Monthly mean flow	1978-2019
Halswell River at Ryan's Bridge	Monthly mean flow, monthly rainfall, annual rainfall	1996-2019
Doyleston Drain at The Lake Rd	Monthly mean flow	1987-2019
Harts Creek at Timberyard Point	Monthly mean flow	2007-2019
Avon River at Gloucester St	Monthly mean flow	1980-2019
Heathcote River at Buxton Terrace	Monthly mean flow	1991-2019
13 Mile Bush	Monthly rainfall, annual rainfall	1963-2019
High Peak	Monthly rainfall, annual rainfall	1958-2019
Ridgens Rd	Monthly rainfall, annual rainfall	1990-2019
Taumutu	Monthly rainfall, annual rainfall	2007-2019
Christchurch	Annual potential evapotranspiration, monthly potential evapotranspiration	1984-2019
Lincoln	Annual potential evapotranspiration, monthly potential evapotranspiration	1960-1987 1990-1999 1999-2019

3.3 Modelling

It is not always possible to have recorded data for all sites of interest or spanning different conditions. So, modelling provides a tool to assess what may have or could potentially occur under a set of defined conditions. There are many different types of models which can be used in water resource studies. In this thesis they are grouped into four broad categories; the categories range in complexity, level of effort required and predictive ability.

Conceptual models

Conceptual models represent a system (often a catchment in water resource studies) by describing the interactions between different parts of the system. The benefit of conceptual models is their simplicity and ease of understanding. However, their application can be limited by the difficulty in making quantifiable predictions.

As conceptual models can be simple to develop and can increase in complexity as the practitioner builds understanding, they often form the first step of developing any of the other three types of models. Conceptual models often have low complexity, can have little effort required to develop, but have limited predictive capability. Section 2.4 describes the conceptualisation used in this thesis.

Physical models

In some instances, it may be possible to create a physical representation of the system being studied. These physical models can provide visual representations of the processes occurring. Physical models are best suited to simulating small areas and limited numbers of processes. While physical models are good for demonstrating the processes occurring in the hydrological system, they are often not practical for many studies.

Analytical models

Analytical models are a category of generally simple models which are based on empirical calculations or relationships. They may not include representations of individual physical processes but may rely on relationships between input and output data. Their ease of application in data scarce areas makes them ideal for preliminary studies; they are often superseded by numerical models as data and interest increases (Zipper et al., 2018).

Numerical models

Numerical models are complex representations of physical systems, which are simulated using time stepping computer code. Numerical models often have a range of parameters which represent physical processes or properties. Parameters can represent a single physical process or property or be lumped to capture a combination of these. Model parameters are adjusted through a calibration process to match modelled outputs with field observations.

Numerical groundwater models often fall into two categories - finite difference or finite element models, which describes their structure and how the partial differential flow equations are calculated. Finite element models use a mesh of geometric shapes to approximate solutions to the partial differential flow equations; finite difference models use a grid approach for approximating these solutions. The MODFLOW code being used in this study is one of the most widely used finite difference groundwater modelling codes.

3.3.1 Model development process

The model development followed in this thesis generally follows the process set out in the diagram in Figure 3.1.

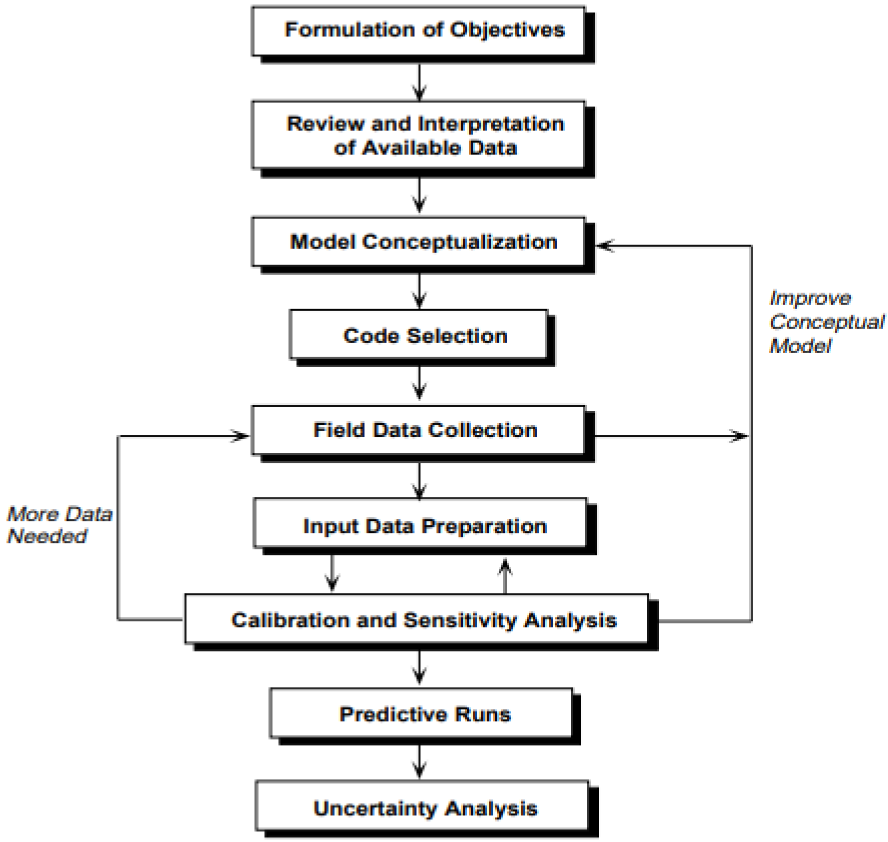

Figure 3.1 Model application process from (Bear et al., 1992)

The structure of this thesis is aligned with Figure 3.1 as follows. The **objectives and aims** of the research are described in section 1.1 of this thesis. The **review and interpretation of available data** is described within the background information in section 2 and continues into the trend analysis described in section 3.2. The **model conceptualisation** has been carried out based on existing literature and studies; this is described in section 2.4. The MODFLOW **code** has been chosen for application in this research and is described in section 2.2 and section 3.4.2. Additional **field data collection** was outside the scope of this thesis and a desktop approach was taken using existing data. These **data were processed and input** into the model as described in section 3.5. The model **calibration** is described in section 3.6**.** **Predictive model runs** have been carried out and used for the scenario testing described in section 4.2.2. **Uncertainty analysis** was not within the scope of this research but could be carried out as part of a future study to refine the model developed for this thesis.

3.3.2 Groundwater modelling guidelines and application

Where possible the model development will comply with the Australian Groundwater Modelling Guidelines (Barnett et al 2012). Resource requirements for different levels of certainty vary, with increased model certainty often requiring much greater levels of development effort and calibration data. As this thesis is a desktop study using existing data sets and utilises commonly available computing hardware, is it acknowledged that not all guidelines are able to be followed. This means that the certainty in model results will likely be lower than those which could be achieved with a targeted field campaign prior to model development. Increased computing resources and study duration would also allow greater certainty in model results; this would allow more complex or computationally intensive modelling to be carried out. This could include uncertainty analysis, which was outside the scope of this research.

3.4 Model development

The intent in this research is to develop a model that can be run on a standard laptop with modern hardware. Models can be developed with high levels of complexity and parameterisation, and with access to supercomputers or cloud computing capabilities these models can be run and calibrated in much shorter timeframes than would be possible on a standard laptop. However, access to high performance computing is not always available and this research aims to work with the tools which are available to most practitioners.

This study focuses on developing a simple numeric surface water and groundwater model capable of capturing the changes in water levels and flows which could occur with changing recharge and abstraction. To do this a steady state model was developed and used to test scenarios for changes in long term average conditions, and a transient model simulation was trialled to investigate if the model can simulate daily changes in flows.

This study takes a simplified approach in acknowledgement of the complexity and time required to produce other surface water and groundwater models, such as the Canterbury Groundwater Model (Weir, 2005, 2007, 2018), which has been developed, refined and used for over 21 years. A similar type of model in the Hawkes Bay region (Rakowski et al., 2018) was developed over a shorter period of time but required a large resource input, including approximately 50,000 hours of processing time for model calibration. It is not intended that the model produced as part of this thesis will be as detailed as the MODFLOW models of Weir (2018) and Rakowski et al. (2018).

3.4.1 Modelling philosophy used in this research

As all models are a simplification of the physical world and are intended to help the modeller understand physical processes, it is important that the model is developed with its intended purpose in mind. As this research was designed to develop a model which could be run without highly specialised computing resources, it was important to have a model philosophy which allowed a useful model to be developed while still being simple and efficient to run on a standard laptop.

Model development was undertaken using a parsimonious approach, by starting with a simple model and building complexity as required. This approach was chosen to prevent over parameterization of the model and to allow the model run time to be as short as possible while still meeting the study objectives. As further detail was added to the model, testing was undertaken to see if the additional detail improved the model. Adding detail into the model often increased the model run times without necessarily benefitting the simulated flows and water levels. If adding additional detail or complexity resulted in significantly longer run times, decreased numerical stability, or did not result in a better model fit, the simpler model was retained.

When undertaking any modelling project, it is important that the modeller understands the trade-offs which are being made between the complexity of the model and the resource requirements to develop the model. For this reason, models are generally built to answer specific questions and it is unlikely that a single model could be developed which is suitable for all possible applications. In this research, the Selwyn River and nearby groundwater is the area of key interest; much of the modelling effort was therefore focused on this part of the model. Models often cover larger geographic areas than their area of interest. This is to avoid the model boundaries interfering with the model results in the area of interest. The areas within the model domain but outside of the area of interest have been of lower priority than areas near the Selwyn River.

3.4.2 Model code used

This research utilises the MODFLOW code, which was developed by the U.S. Geological Survey and is a package of code for computer simulation of groundwater processes (Harbaugh, 2005; McDonald & Harbaugh, 1984). MODFLOW is a finite difference, physically based, three-dimensional gridded model, and includes packages which simulate hydrological stressors such as groundwater pumping, recharge and interactions between surface water and groundwater.

Various iterations of MODFLOW have been developed over the years. This research used MODFLOW-NWT to simulate surface water and groundwater under steady state and simplified transient conditions. MODFLOW-NWT has been chosen as this version includes a newton solver which allows model cells to dry and re-wet without causing the model to become numerically unstable. This ability for cells to dry is very important in simulating a catchment such as the Selwyn, where there are large variations in depth to groundwater.

The MODFLOW model code is open source and can be run with a range of different interfaces. The different user interfaces provide different features and assist with processing the many different model files. The graphical user interface GMS (Groundwater Modelling Systems) version 10.4 was used in this study. MODFLOW models can be developed, visualised, and calibrated using GMS. This proved a useful tool when learning MODFLOW, as the GMS interface provided model checks to ensure that errors were identified early, and the visualisation of the model inputs allowed a simple ‘sense check’ of input data and simulation results. This interface requires the purchase of a licence to build and run models, but the native MODFLOW files can be exported and converted to use in other interfaces or run directly via coding such as the Python package for MODFLOW, FLOPY (Bakker et al., 2016).

3.4.3 Model domain

The area simulated in the model is referred to as the model domain. The model domain used in this research encompasses the plains of the Selwyn/Te Waihora Catchment described in 2.3 and extends to the Waimakariri River to the north and the Rakaia River to the south (Figure 3.2). The inland boundary of the model domain is at the 300m elevation contour; this excludes the upper parts of the Selwyn River as these areas have little groundwater resources. The NIWA flow recorder on the Selwyn River at Whitecliffs is near to the inland model boundary and is considered to capture all the flow from the portion of the catchment which is excluded from the model domain. The coastal boundary extends approximately 3km offshore to reduce the model boundary impacts on lowland streams which are simulated near the coast. As Banks Peninsula has steep slopes and low permeability volcanic geology, which constrains groundwater movement, the eastern boundary of the modelled plains is the 50m elevation contour.

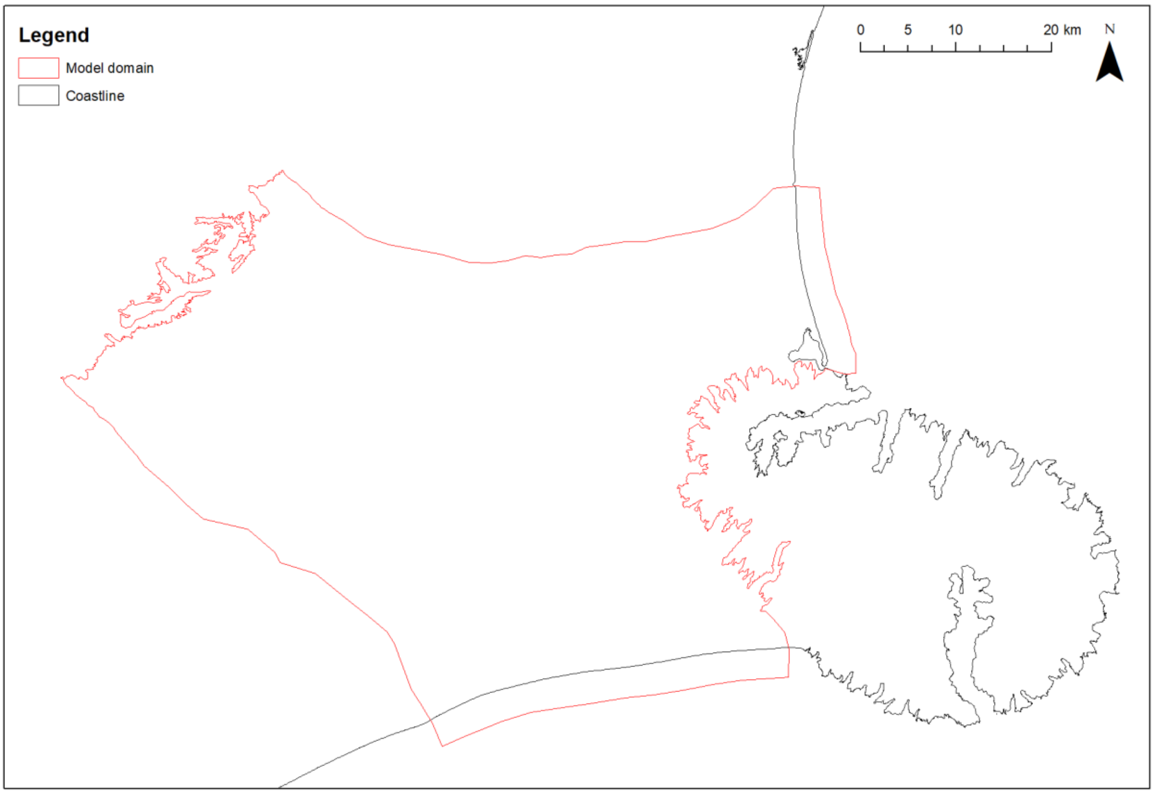

Figure 3.2 Domain of the MODFLOW model used in this research.

3.4.4 Simulation period

Throughout the model development, inputs were generated for the 10-year period 1 July 2009 to 30 June 2019. This period was chosen to represent steady-state conditions as it includes both wet and dry seasons and is recent enough that the required data sets were available. This period also represents a period of reasonably stable land use within the catchment as much of the development and intensification occurred prior to this. Within the model period there have been some increases in irrigation areas and additional water sourced from the alpine rivers brought into the catchment; this has occurred with the development of the Central Plains Water irrigation scheme (described in section 2.3.1). Figure 2.6 indicates that water allocation has been stable for the simulation period, with a small decline in allocation occurring near the end of the simulation period.

3.5 Model structure

Both the model structure and parameterisation influence how a model performs. The model structure is the components of the model and how the model is built. The model parameterisation is the way in which parameters are defined, including which values are entered into the model to represent the physical conditions. The model structure is not changed through the calibration process, but the parameters are adjusted to match the simulated flows and levels to observations. This section focuses on the structural components of the model build. A description of the model parameterisation is included in Section 3.6.

3.5.1 Model horizontal spatial discretisation

The model has been developed with a 1km x 1km uniform grid. The grid consists of 86 rows and 62 columns and includes 14,470 active cells (Figure 3.3). The total number of model cells is 26,660, including inactive cells. The model grid has been rotated by 40 degrees to align with the dominant groundwater flow direction. All model layers have the same horizontal extent and number of cells. Model cells occurring in the narrow valleys at the inland and Banks Peninsula boundaries were made inactive if they only had limited contact with other nearby model cells.

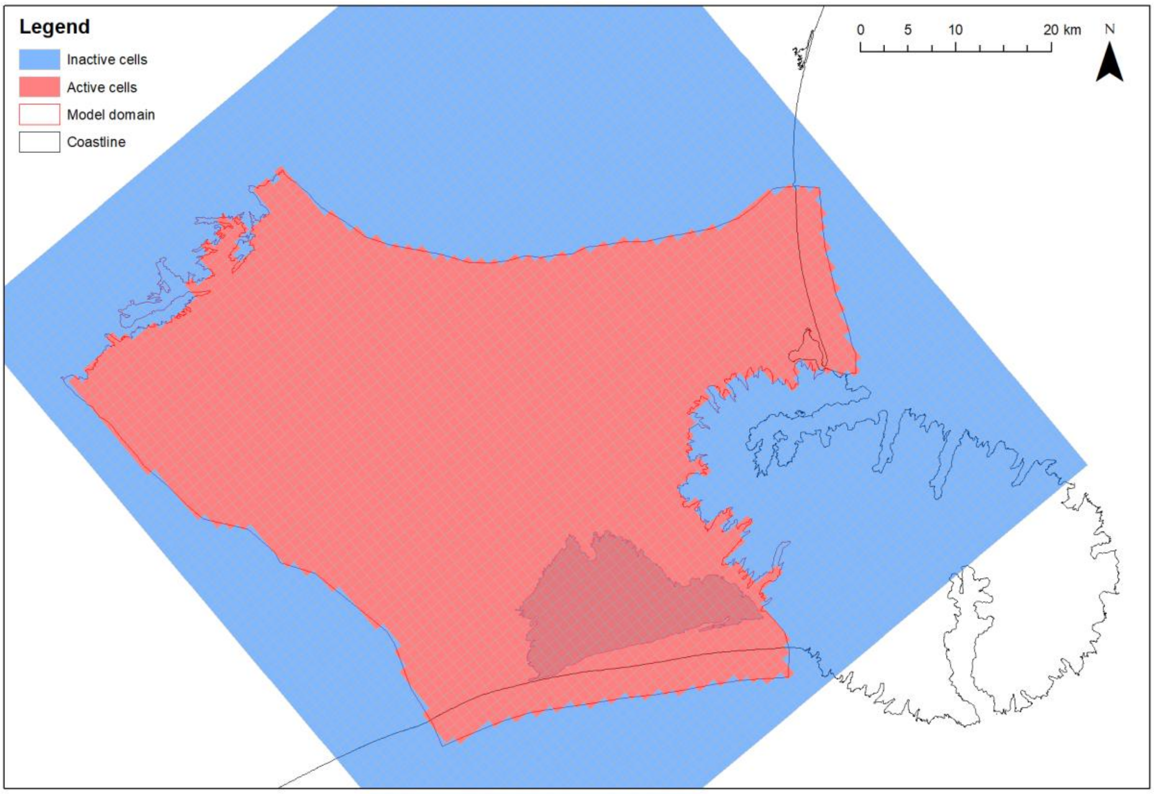

Figure 3.3 Model grid and active cells within the model domain

3.5.2 Model vertical discretisation

The model has been discretised into 5 numeric layers. Early iterations of the model development were tested using 15 numeric layers, but this resulted in excessive model run times and convergence issues related to the upper layers wetting and drying. Layer elevations have been based on the geological model for Eastern Canterbury developed by GNS (Begg 2015). The base of the MODFLOW model domain has been determined using an interpolation of the contours of the bottom of the quaternary deposits in the Canterbury Plains (Jongens 2011). The land surface has been derived by extracting model cell elevations from the 25m Canterbury Digital Elevation Model (DEM).

The model layers cover elevations from 300m above sea level down to approximately 550m below sea level. Plots of elevation of the top and bottom of model layers are included in Appendix 1.

3.5.3 Recharge

Land surface recharge (LSR) is a major input to the water balance in the Selwyn/Te Waihora Catchment. LSR has been modelled outside of the MODFLOW model and applied as an input via the MODFLOW Recharge Package (RCH). To estimate recharge, a soil moisture balance model was developed in Microsoft excel, based on the GDA (Groundwater Data Analysis) eigen model tools LSR component (Bidwell & Morgan, 2002). This LSR and soil moisture balance was a daily model which was run from 1/7/2008 to 1/7/2019. A one-year warm up period (from 1/7/2008 to 30/6/2009) was used, to remove the influence of initial conditions on results.

Recharge has been calculated for each of the active model cells within the domain (Figure 3.3) excluding those within the coastal area or covered by Te Waihora. The soil moisture balance requires inputs of climate, irrigation information and soil properties.

Climate zones are defined using Thiessen polygons with 5 rainfall sites (Figure 3.4). Due to the lack of ET sites, uniform ET from Lincoln has been used for all model cells. The five sites where rainfall was used are Selwyn at Whitecliffs, Selwyn at Ridgens Road, Christchurch at Botanic gardens, Lincoln at Broadfields, and Lake Ellesmere at Taumutu.

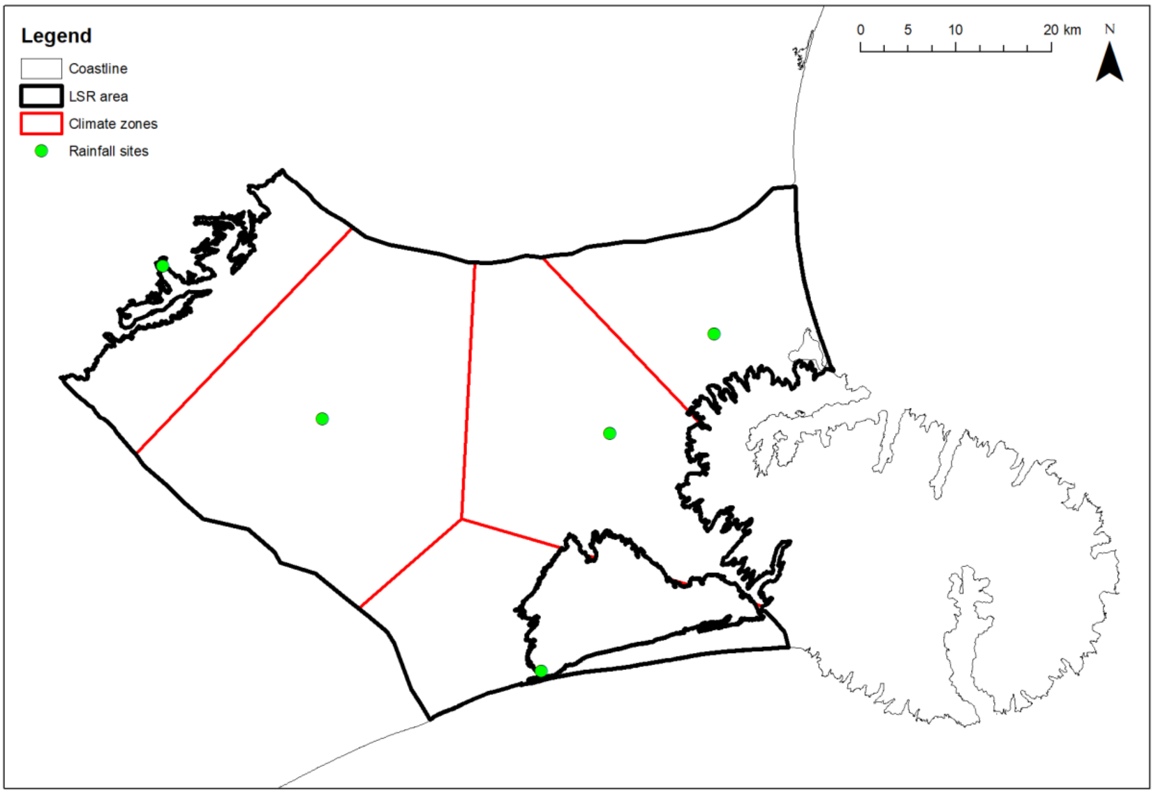

Figure 3.4 Climate sites and Theisen polygons used for recharge calculation.

The amount of LSR that an area receives is influenced by whether irrigation is occurring or not. A piece of land with irrigation will recharge more than the same piece of land managed as dryland. To capture this within the modelling, each cell was designated as either dryland or irrigated. As the model cells are 1km x 1km, not all of a cell is always irrigated. Using the GIS information of irrigation areas in Canterbury (Figure 2.8), testing was carried out to determine what percentage of a model cell needed to be covered by irrigation for it to be counted as an 'irrigated cell'. By matching the total area within the model domain covered by irrigation (based on the GIS information) with the sum of the irrigated cells, it was found that mapping cells with more than 70% of the area as irrigated resulted in the same total irrigated area within the model. Figure 3.5 shows the cells mapped as irrigated based on having 70% irrigation coverage.

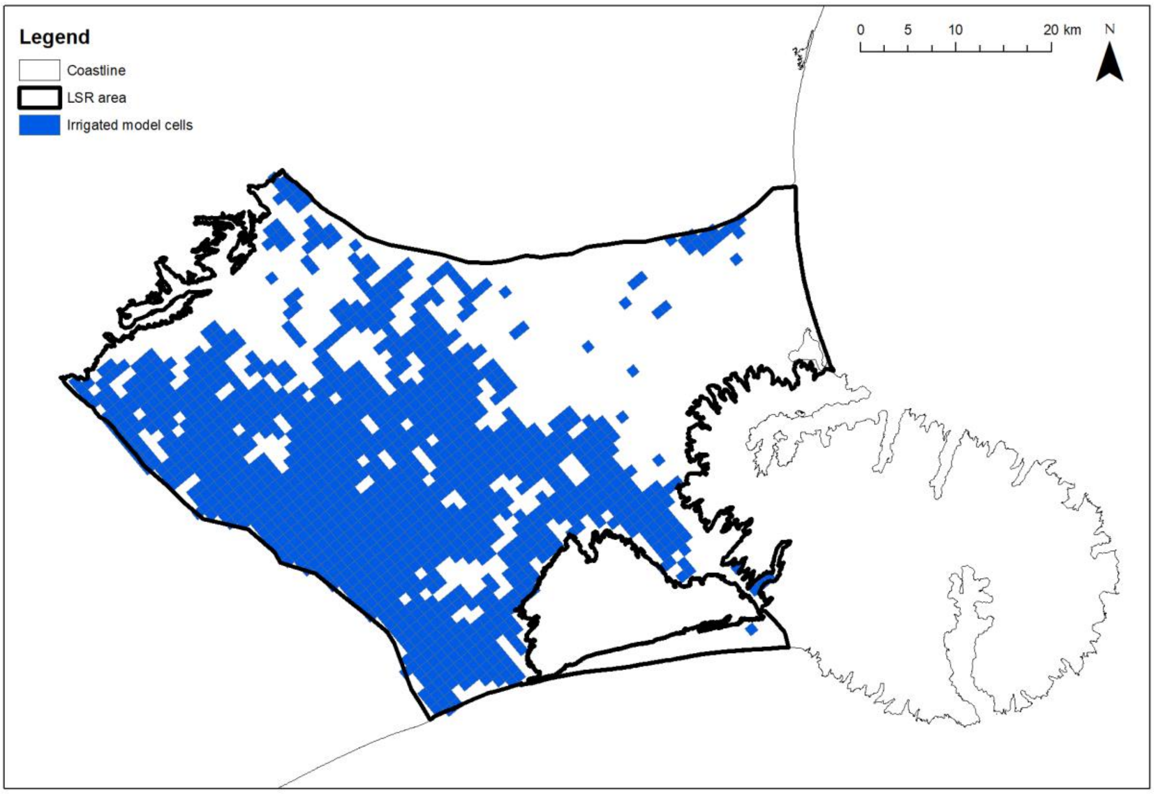

Figure 3.5 Model cells identified as irrigated land for recharge calculation.

The soil type within the model cell also influences the recharge and is a key component of the soil moisture balance. As soil is very variable across the model domain, it has been grouped into five different categories based on the profile available water (PAW) from S-map (Lilburne et al., 2012). These five categories are shown in Table 3.2 and have been assigned soil codes and PAW (mm) which align with categories reported by the regional council.

Table 3.2 Soil classsifiction and PAW used for recharge calculations

Soil name	Code	PAW range (mm)	PAW modelled (mm)
Extra light	XL	0-50	50
Very light	VL	51-80	65
Light	L	81-110	95
Moderate	M	111-150	130
Deep	D	>150	150

The distribution of the different soil classifications, and therefore soil PAW, is shown in Figure 3.6. This shows the deeper soils with the largest PAW occurring lower down the catchment and the inland plains having lighter soil types with lower PAW.

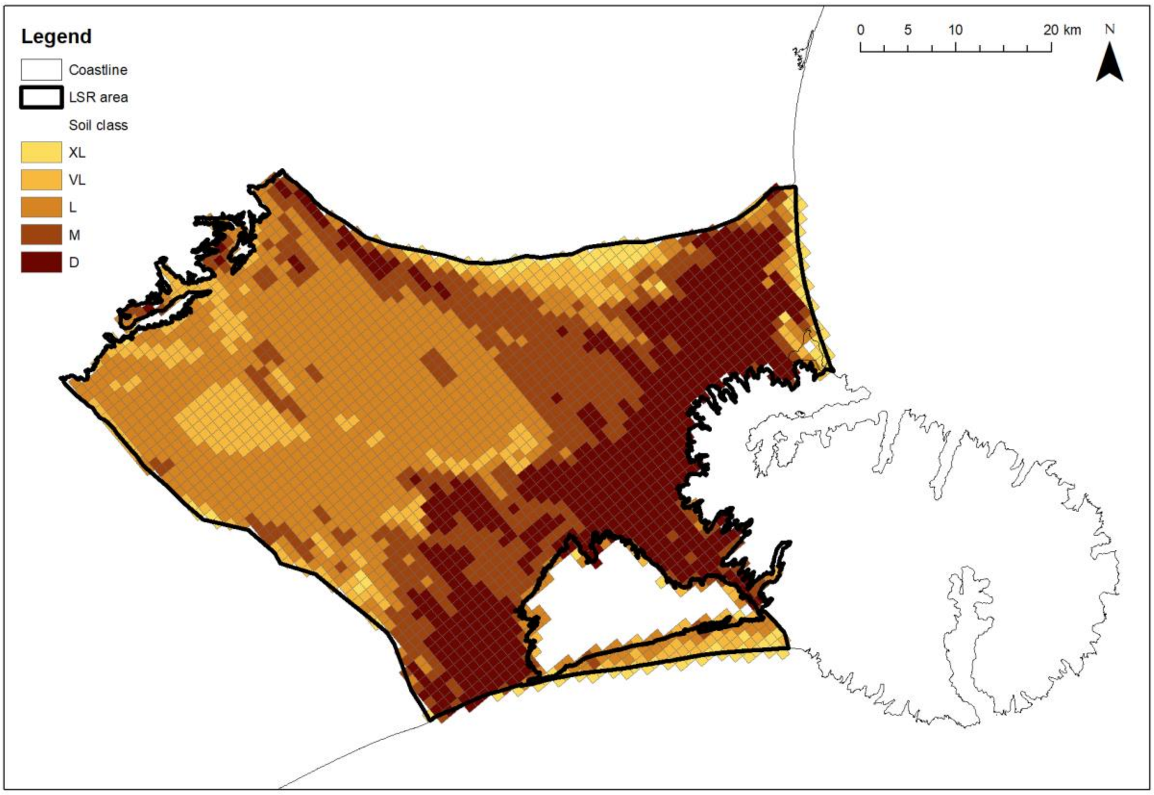

Figure 3.6 Soil classifications used for recharge calculations.

Based on these combinations of climate, irrigation and soil type, each cell is given a classification. This resulted in 50 different possible combinations, 46 of which occurred within the model domain.

The soil moisture balance model calculates a daily timeseries of soil moisture by adding rainfall and subtracting evapotranspiration (calculated using the evaporation reduction function and data from the Lincoln climate site). In cells that are irrigated, irrigation is applied at 5 mm per day from when soil moisture dropped to 50% of the field capacity until soil moisture reached 90% of field capacity. Drainage from this soil moisture balance was aggregated to an annual recharge depth for each combination of soil, climate, and irrigation. The annual land surface recharge depths are shown in Figure 3.7.

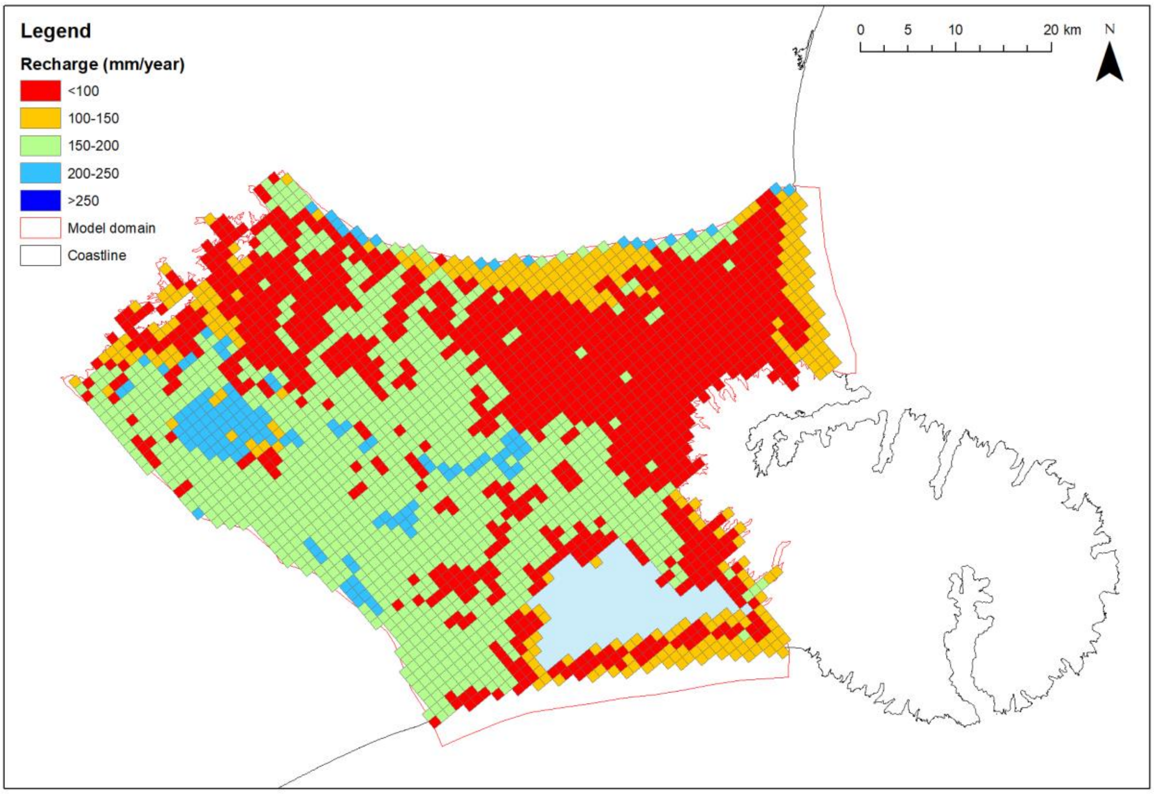

Figure 3.7 Annual recharge calculated for model cells using the soil moisture balance.

In addition to LSR, the groundwater can be recharged from surface water bodies. The natural waterbodies, such as streams, river and lakes are captured in the MODFLOW model. However, the Selwyn/Te Waihora Catchment has a large network of water races which lose much of their flow to the groundwater. The water race network is described in section 2.3.1.4 and shown in Figure 2.4. To capture the recharge contribution of these races, the cells that have water races crossing them have been identified in Figure 3.8. As there are three water race schemes within the model domain, these have been mapped separately.

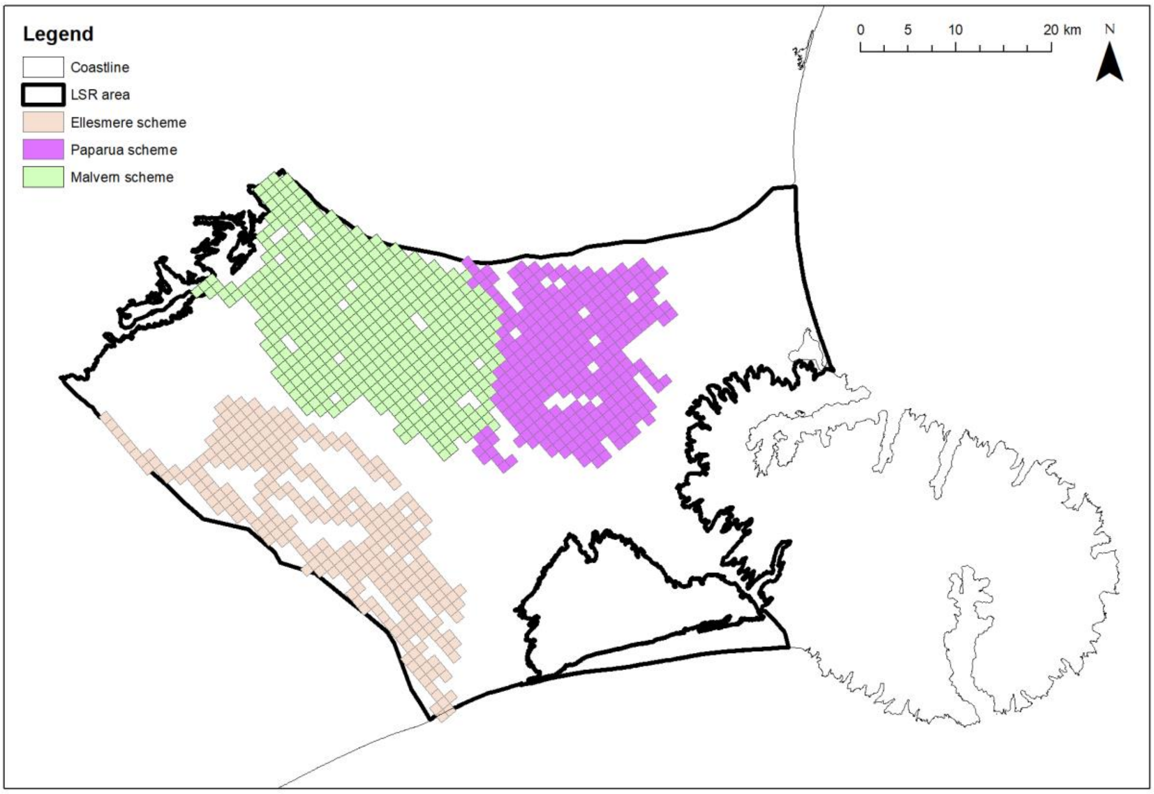

Figure 3.8 Model cells identified as intersecting each of the water race schemes.

To estimate the additional recharge occurring due to these races, it was assumed that 80% of the water entering the races is lost to groundwater. For each of the water race schemes, 80% of the consented volumes is distributed evenly across the number of model cells covered by races. The Ellesmere scheme area has 0.46mm/day added to the recharge to represent race losses. The Paparua and Malvern schemes have 0.30mm/ day and 0.17mm/day of additional recharge, respectively.

Combining the LSR from the soil moisture balance model (Figure 3.7) and the additional recharge from the race networks, gives the total recharge depths for each model cell, shown in Figure 3.9. This recharge layer has been applied to the top of layer 1 in the MODFLOW model. The recharge generated using the simple soil moisture balance in this study results in smaller recharge depths being applied, when compared to the more detailed recharge calculations used by Weir (2018).

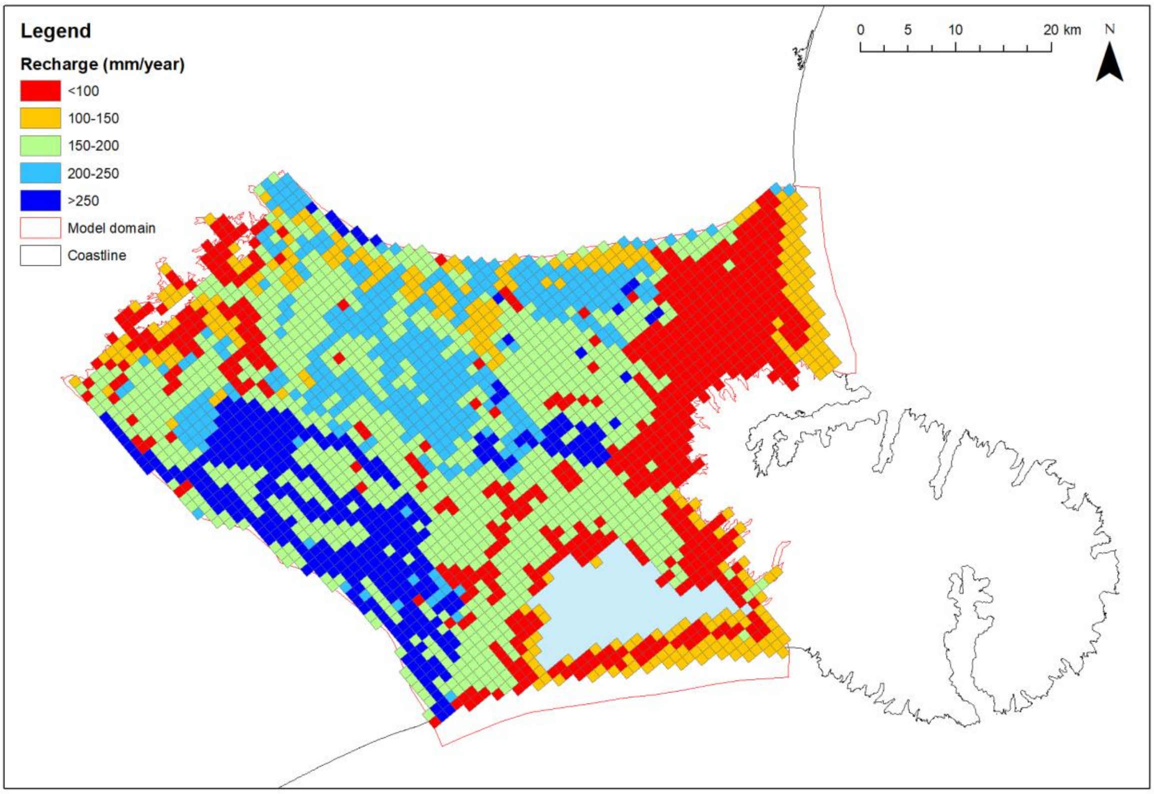

Figure 3.9 Annual recharge for model cells combining the land surface recharge and water race losses.

3.5.4 Geology

Geology influences the occurrence and behaviour of groundwater; this is true within the MODFLOW model and the physical environment. To simulate groundwater, a model must include some representation of the geology and aquifer parameters.

When bores are drilled the materials in the borehole are logged to provide a record of the different strata across the depth of the bore. Within the model domain, 16,721 bore logs were identified with 130,823 strata records. Developing a geological model using these strata records was considered, using the Leapfrog geological modelling software and the GMS geological surface builder. As there are many different strata types it became evident that this approach was very reliant on how bore logs are simplified into a smaller number of categories and how drillers have classified strata when recording bores. Building a detailed geological model was abandoned due to the very long computation times required to use the GMS geological model builder and the licence requirements of specialist geological models such as Leapfrog, combined with the uncertainty associated with the strata categorisation.

The Begg et al. (2015) geological model covers much of the eastern parts of the model domain, and includes 10 geological formations including four aquitard formations. The different geological formations are described earlier in section 2 and Table 2.1. The low permeability aquitard formations cover much of the eastern part of the model domain. The extent of the aquitards modelled by Begg et al. (2015) are shown in Figure 3.10.

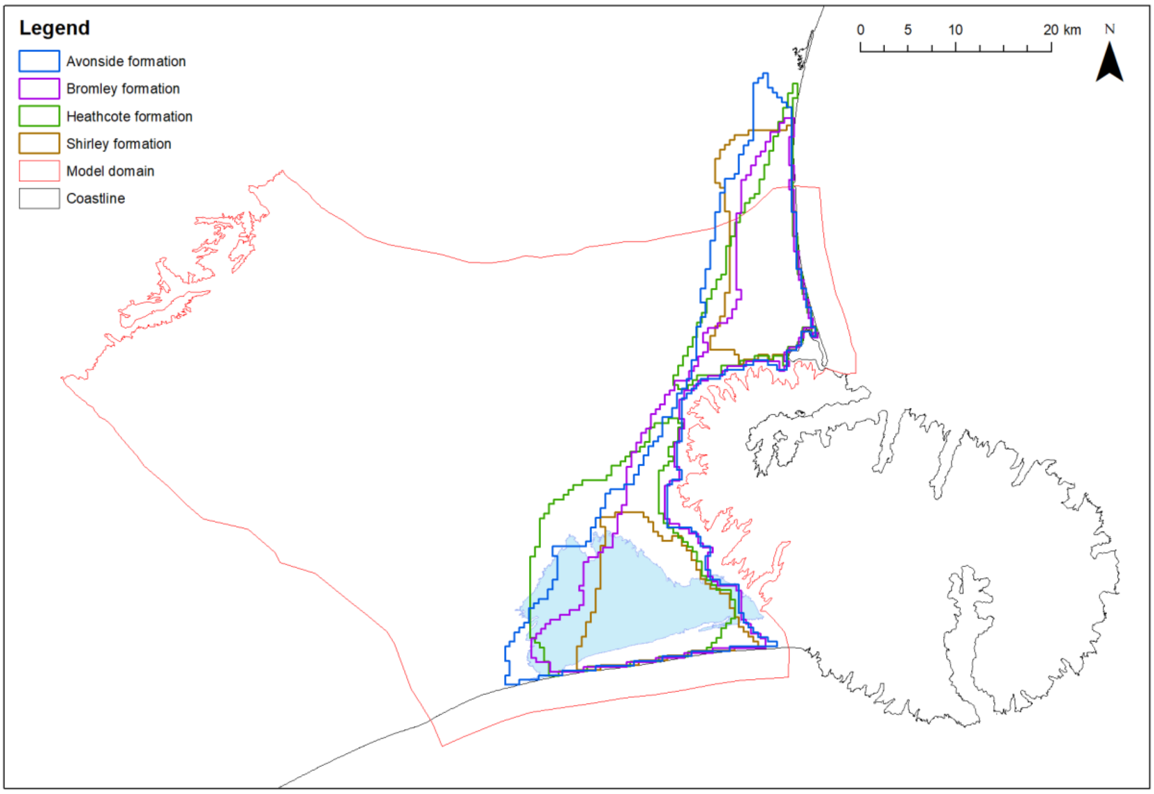

Figure 3.10 Spatial extent of the eastern Canterbury aquitard formations, from Begg et al. (2015)

Initial model testing included setting separate zones in each layer to reflect the horizontal extent of the aquitard layers near the coast. However, this approach was replaced by using pilot points for each layer and allowing a range of hydraulic parameters to be assigned across the layer. This allows for the variability of the physical materials in each layer to have a range of hydraulic conductivities rather than applying a bulk conductivity across each zone or representing average hydraulic properties over the entire layer. Further details about the pilot points and calibration of hydraulic conductivity are included in section 3.6.

3.5.5 Water abstraction

Water abstraction has been included in the MODFLOW model using the Wells Package. Within the model domain there were 3,234 water abstraction points (WAPs) which were active as of 30 June 2019 according to the Environment Canterbury consents database. These WAPs represent an authorisation to abstract water at a known location, at a defined rate. The locations of the WAPs included in the modelling are shown in Figure 3.11. Within MODFLOW two wells cannot occur at the same location. This causes some issues as multiple WAPs may authorise takes from the same physical well. In these cases, any subsequent WAPs were shifted 1m in the x direction to resolve the issue of WAPs being in the same location.

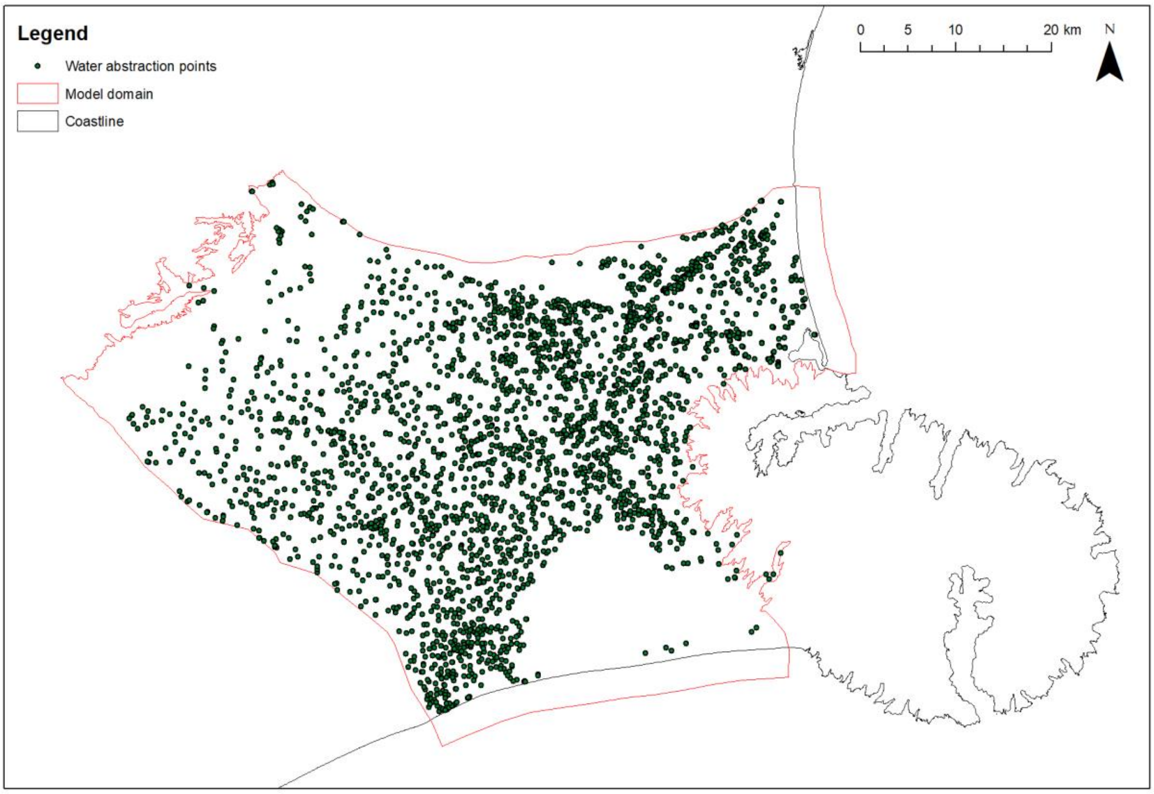

Figure 3.11 Water abstraction points within the model domain

As the WAPs included in the model are abstractions occurring from groundwater, they also have a depth location relative to the land surface. The depth at which WAPs are abstracting water has been based on their well depth and screen depth. The Wells Package assigns the abstraction point in 3D within the model grid based on its X and Y directions, and the screen depth of the well. If there was no screen depth in the well record for a WAP, the screen was assumed to cover the bottom 3m of the well. Each WAP therefore has an X, Y, Z location and rate of take. As described in section 2.3.2, approximately half of the authorised water is actually abstracted (Rajanayaka et al., 2009; Sanders, 1997). Therefore, based on this the abstraction rates were set to 50% of the maximum allowable rate for each WAP. This averaging does not capture the time varying nature of water use, both between seasons and within a single season.

3.5.6 Surface water bodies

MODFLOW has a range of different packages capable of representing surface water features. Within this research the Streamflow Routing 2 Package (SFR2) (Niswonger & Prudic, 2010), the River Package (RIV), the Drain Package (DRN) and General Head Boundaries (GHB) have all been used to represent different features. Each of these have different input requirements and are capable for simulating surface water in different ways. Combining these different model components allowed focus on the Selwyn River while still including other distant features in a more simplified way to reduce computational load.

3.5.6.1 Streams

To capture the surface water-groundwater interactions, the Selwyn River has been modelled using the Streamflow Routing 2 (SFR2) Package in MODFLOW (Niswonger & Prudic, 2010). This package allows interaction to be modelled between the stream and groundwater system through an unsaturated zone beneath the river. The SFR2 Package builds on the previous Streamflow Routing (SFR1) Package (Prudic et al., 2004) which was able to simulate surface water-groundwater interactions in areas with shallow unsaturated zones. As the SFR2

Package increases the computation complexity of the model calculations, it has only been used on the Selwyn River, its tributaries, and the Irwell River. The reaches that have been included in the model are shown in Figure 3.12. The reaches representing the Selwyn River and its tributaries extend to the western edge of the model domain and flow to the general head boundary representing Te Waihora. Inflows to the Selwyn River and tributaries have been applied at the most western reach of each river. The inflows for the steady state model were the average flows for the model period. As the Irwell River is spring-fed and emerges from within the model domain, no inflow is specified for this.

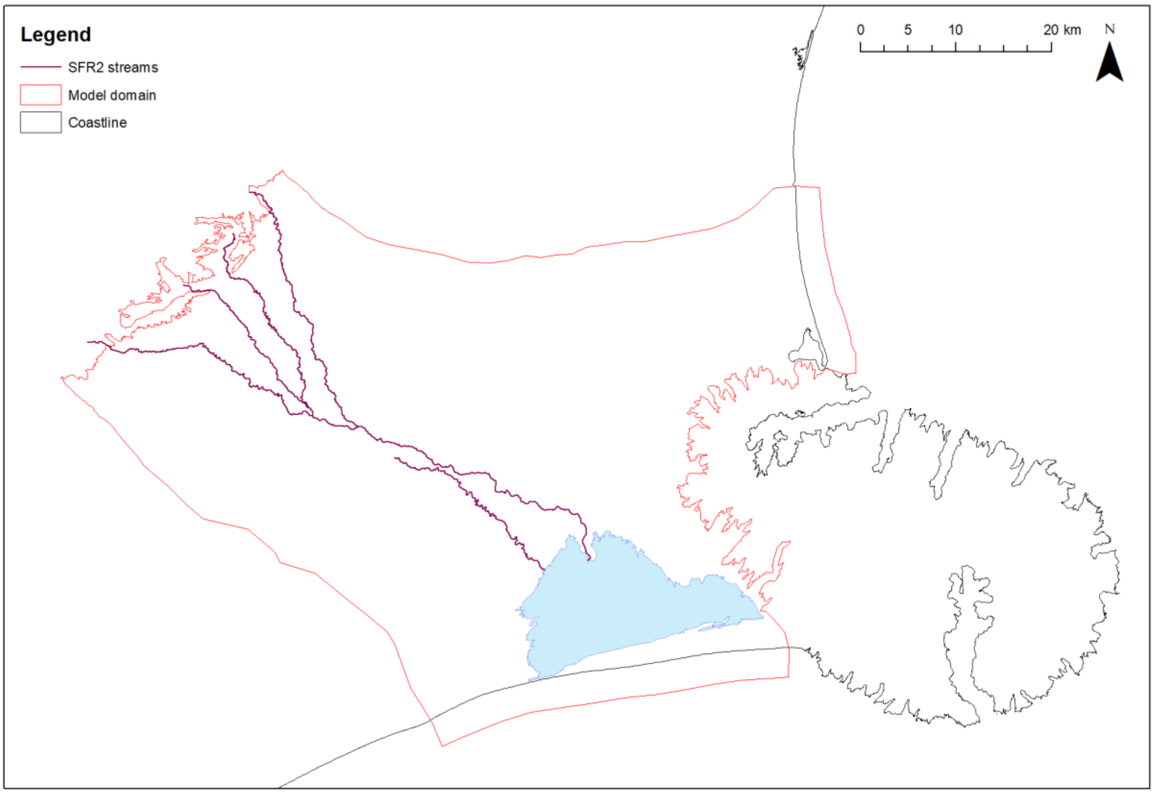

Figure 3.12 SFR2 reaches included within the model, representing the Selwyn River, its tributaries, and the Irwell River.

The cross-section flow calculation method within the SFR2 Package has been applied for simulating flow within all the SFR2 reaches. This method requires cross sections for each reach modelled. These cross sections need to have eight points and the elevations for these were extracted from LiDAR data sets available for the study area. Cross sections were extracted from the LiDAR data at approximately 1km spacing at locations where the river was a single channel. Two LiDAR flight data sets were used for extracting cross section and streambed elevations. These were survey AAM_SelwynLiDAR_2015_2016 (Environment Canterbury et al., 2015), flown on 5/10/2015 (which covers the upper Selwyn River and Tributaries) and survey NZAM 10027 Timaru Town and Coast (Environment Canterbury, 2010), flown on 19/03/2010 (which covers the lower Selwyn River and Irwell River).

LiDAR uses imagery to capture high resolution topography. As the lower Selwyn River is deep and slow moving, a large portion of the cross sections of interest were not captured by LiDAR. To adjust for this, gauging cross sections at flows close to mean flow were appended to the LiDAR cross section to extend the cross section below the water surface. LiDAR data are used for the cross section above the water surface and the gauging cross section has been used below the water surface. This was less of an issue in the remainder of the Selwyn River where the river is less constrained and much shallower. The sites where eight-point cross sections have been extracted from the LiDAR data and applied to the SFR2 network are shown in Figure 3.13.

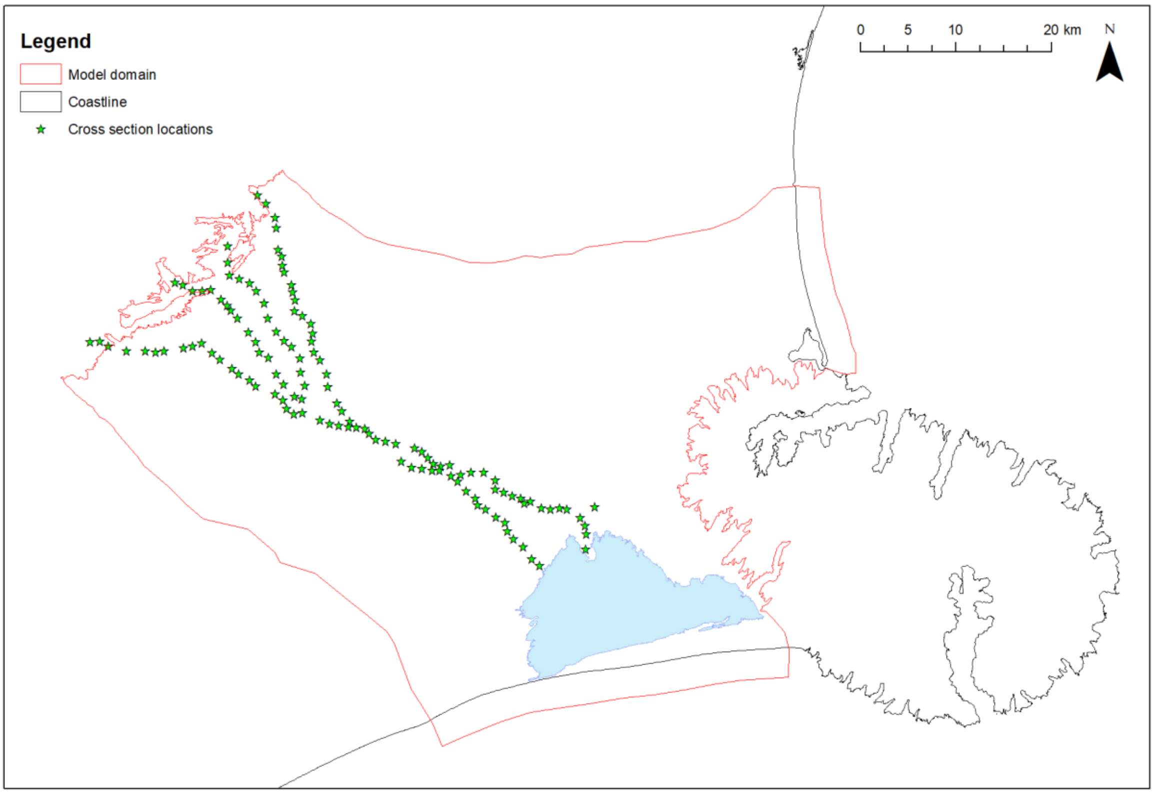

Figure 3.13 SFR2 cross section locations

Mapping the SFR2 network to the MODFLOW grid resulted in 356 SFR2 cells. In each of these, flow can be simulated based on the surrounding groundwater conditions, stream bed properties and flow routed on the surface from neighbouring up-gradient cells. The Manning's roughness represents the resistance to surface flow and the roughness of the streambed and banks have been assigned as 0.03 for the wetted channel and 0.045 for the overbank flow, following Hicks & Mason (1991). The stream bed conductance influences how easily water passes between the surface and subsurface. As this was not something that there were field measurements or textbook values for, this conductance term was used as a calibration parameter to control losses and gains for the SRF2 reaches.

3.5.6.2 Drains

The model domain includes many other lowland streams which are fed by groundwater discharges. Using the Drain Package (DRN) (Harbaugh, 2005) within MODFLOW allows a simpler simulation of these waterbodies than using the SFR2 Package. The Drain Package allows flows to be simulated from the groundwater system but does not allow surface flow to be lost to groundwater or be routed along a waterbody. In MODFLOW, groundwater discharges to drain cells but water in the drain does not recharge back to the groundwater system. That is, water that enters drains is removed from any further interactions in the model.

Drain cells can be used to represent open-channel drains or below-surface drainage features and require less knowledge of the waterway than is required for the SFR2 Package. The main inputs for drainage features are drain elevations and drain conductance. The drain evaluations were simulated by generating a Triangular Irregular Network (TIN) 2m below the land surface for the DEM. This represented the base of the drains being 2m below the top of the model cells while capturing the gradient change in drain level which occurs within the 1km x 1km cells.

Fourteen waterways have been included in the MODFLOW model as drain features, these are shown (grouped by colour) in Figure 3.14. These waterways have been mapped to include both natural spring-fed waterways and artificial drainage networks, including those operated by the district and regional councils, shown in Figure 2.5. The drain conductance for each of these was used as calibration parameters and were adjusted to match simulated flows from areas of drain cells with observed flows in those waterways. The calibration and model fit for drain cells is described in section 3.6.

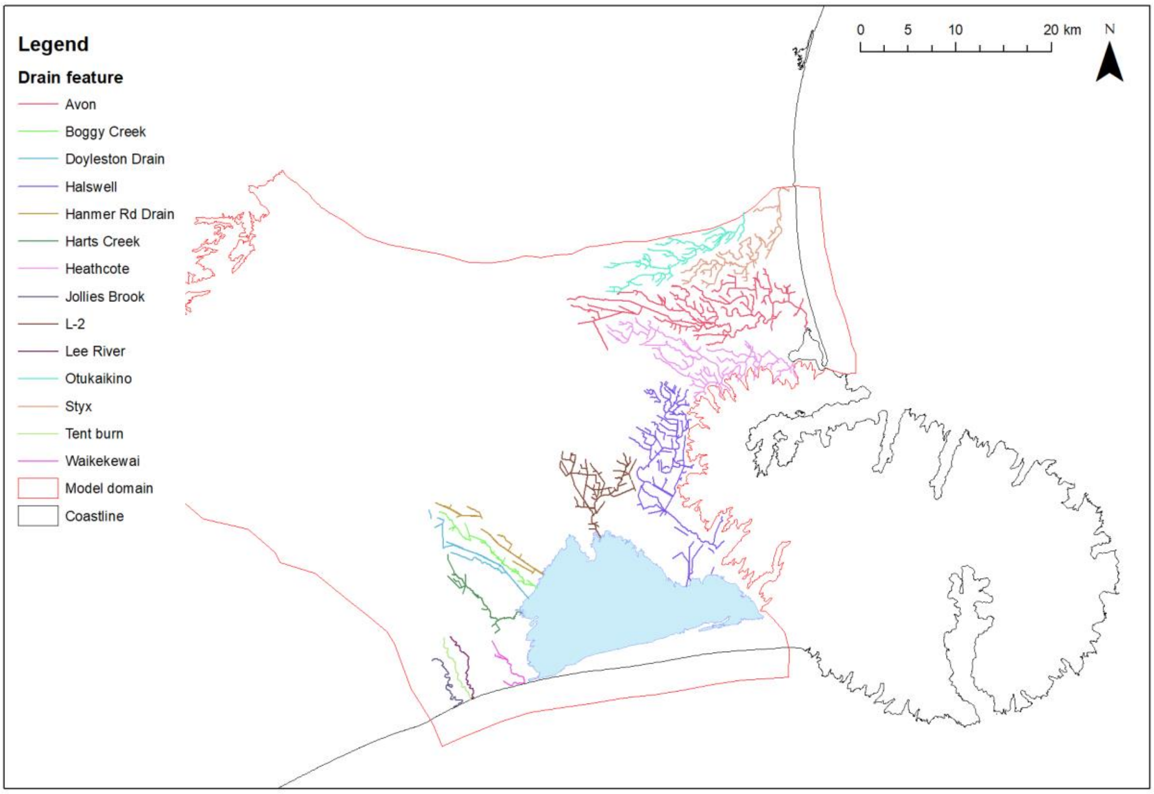

Figure 3.14 Waterways simulated using the Drain Package.

3.5.6.3 Coast, coastal lakes, lagoons, and estuary

The model domain includes Te Waihora, the Avon/Heathcote Estuary, Brooklands Lagoon, and other small coastal waterbodies. The area of ocean within the model domain and the lakes, lagoons and estuaries are included in the MODFLOW model as general head boundaries (GHB) (Harbaugh, 2005). The elevation of the GHB was set at top of layer 1. The coastal general head boundary has been applied to the top layer and the most coastal model cell in each of the other layers. The conductance of 9999m/day has been set to reflect an un-impeded flow offshore. Te Waihora has been included as a general head boundary applied to layer 1 with conductance used as a calibration parameter. If Te Waihora was the focus of this model it could be included in more detail using the Lake Package (LAK). The remaining small waterbodies included as general head boundaries have an assumed conductance of 0.0002m/day applied. Figure 3.15 shows the location of the general head boundaries applied within the MODFLOW model.

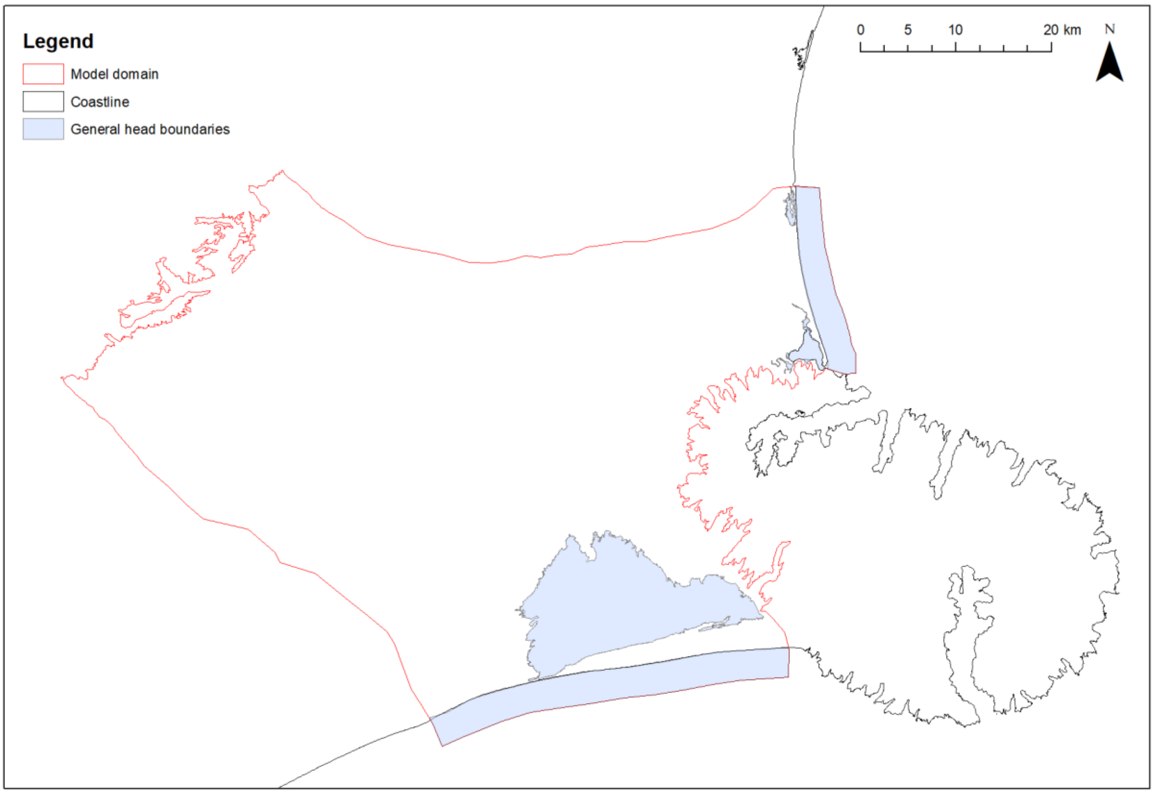

Figure 3.15 Areas where general head boundaries have been implemented.

3.5.6.4 **Alpine *Rivers***

The Rivers Package (RIV) (Harbaugh, 2005) has been used to represent the Waimakariri and Rakaia Rivers. Each of the rivers were split into reaches to reflect the different areas, and to allow variable conductance down the length of each river. The bed conductance for each reach was used as a calibration parameter and is described further in section 3.6. Bed elevations for these reaches were simulated as being 3m below the top of the model cell.

3.6 Steady state model calibration

The process of adjusting model parameters to match simulated flows and water levels with observations is referred to as model calibration (Barnett et al. 2012). Calibration can be an iterative and time-consuming process for complex models. Increasing the number of observation sites that the model is calibrated to increases the confidence in the model outputs. Having observation points distributed across the areas of interest provides some certainty that the model is reliable in that area, but also results in increased resourcing requirements for calibration. The modeller must determine the appropriate balance between simple models and highly parameterised complex models based on the data available and the questions being asked of the model. In this research, 44 calibration parameters were defined; these are shown in the tables in Appendix 2. These parameters were adjusted to match simulated flows in lowland streams with observations and simulated groundwater levels with observations. Calibration targets were set at the mean of observed flows or water levels recorded over the simulation period.

The locations of the groundwater observation points used for calibration are shown in Figure 3.16. These points represent Environment Canterbury's groundwater level recorders within the model domain, and the regularly measured manual groundwater level sites. Groundwater levels near the Selwyn River and coastal parts of the model were calibrated to a more constrained target range than those inland and far from the Selwyn River. This reflects the focus of the model being on the Selwyn River and shallow groundwater.

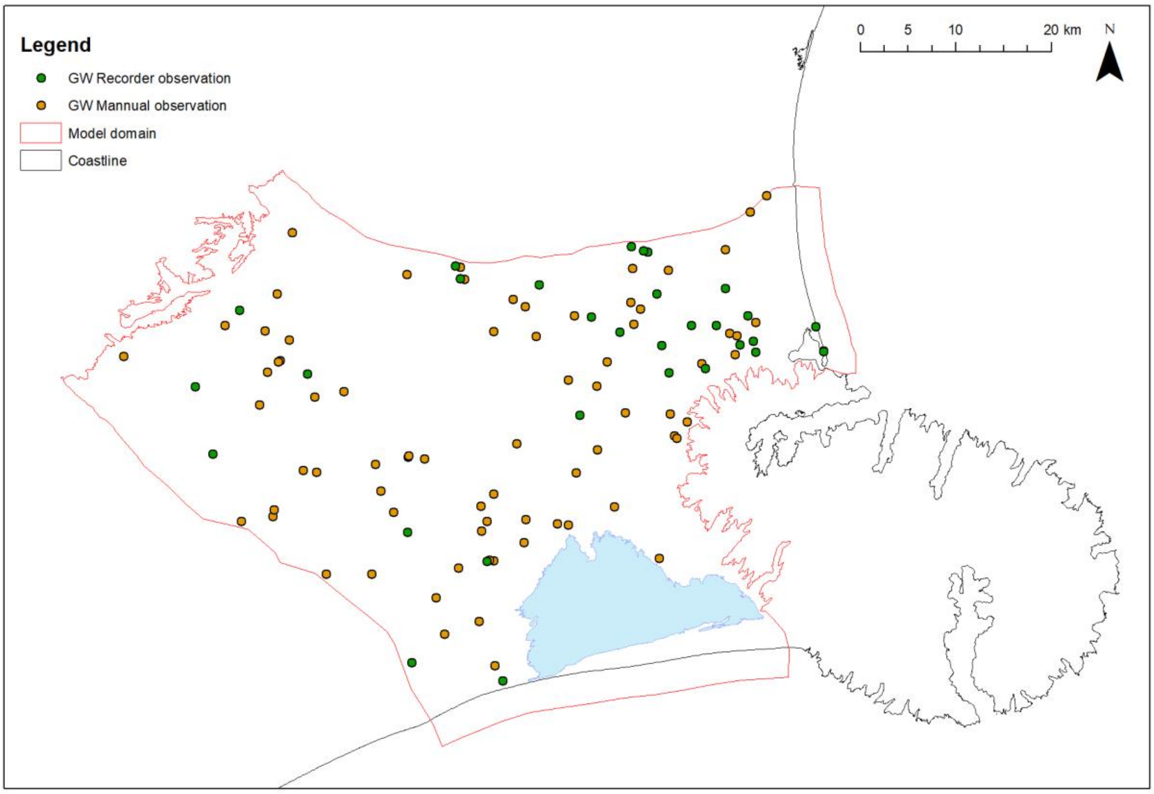

Figure 3.16 Groundwater level observation used for calibration.

Surface water flows were also calibration targets used for determining appropriate parameters. Target flows were set for each of the drain features and a calibration target of within 10% of the mean flow was used. Calibrating to the SFR2 reaches in the Selwyn River was completed manually with flows being matched to those observed at Coes Ford and the dry reaches being matched with known locations.

Hydraulic conductivity was calibrated for each layer using pilot points. 49 points, distributed uniformly over the model domain were used to estimate horizontal hydraulic conductivity in each of the model layers. The pilot point distribution is shown in Figure 3.17. Hydraulic conductivity was estimated for each of these points using the automated parallel parameter estimation PEST (Doherty & Hunt, 2010). Hydraulic conductivity was interpolated between the pilot points to create a smoothed surface representing the variability occurring spatially. The range of conductivity that the calibration allowed was chosen to represent the types of geology expected to be found within each numeric layer, based on Begg et al. (2015).

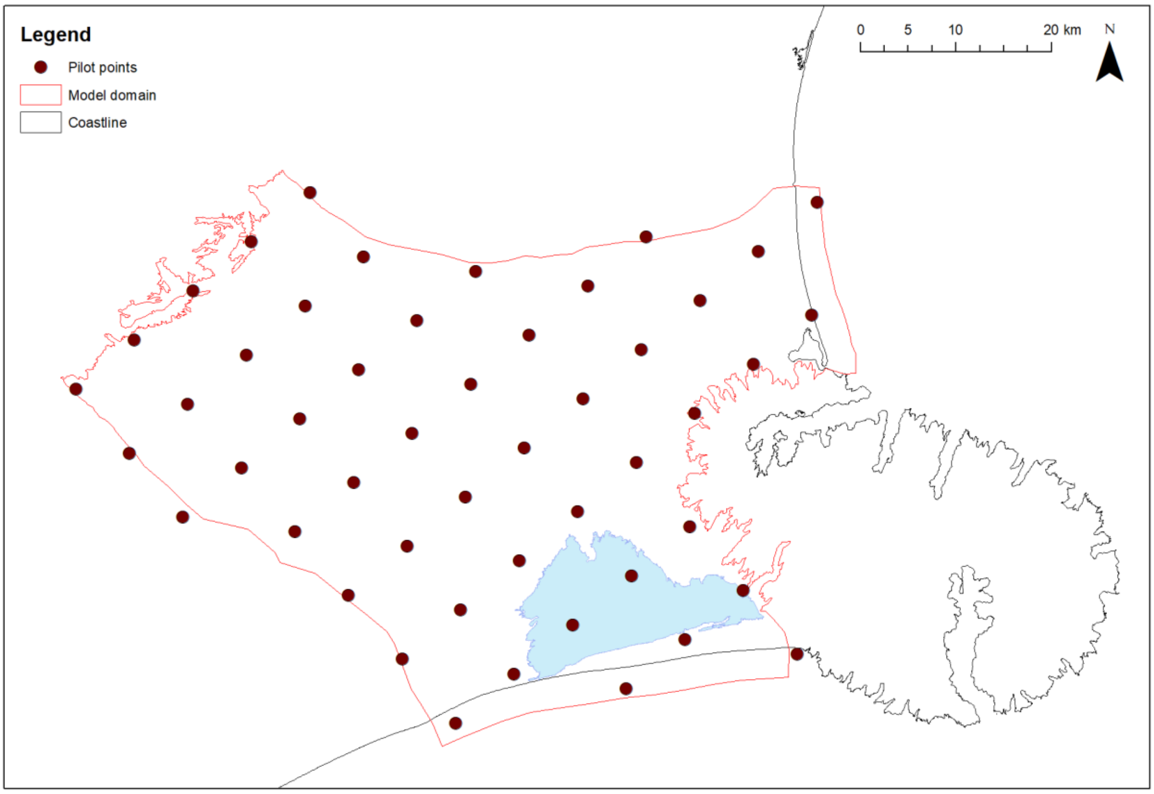

Figure 3.17 Pilot point locations used for calibration.

Table 3.3 shows the range of different parameter types used in the MODFLOW model. The final parameters resulting for the steady state calibration process are shown in Appendix 2.

Table 3.3 Summary of the different type of parameters

Parameter	**unit**	**Method**	**Number of parameters**
Horizontal hydraulic conductivity	m/day	Pilot points	245
Vertical anisotropy	-	By Layer	5
Specific yield	-	By material type	1
Specific storage	1/m	By material type	1
River conductance	m^2/day	Major reaches	10
Stream conductance	m^2/day	Reach by reach	8
Drain conductance	m^2/day	Drain by drain	16
Coastal conductance	m^2/day	Two zones	2
Lake conductance	m^2/day	single value	1

3.7 Proof of concept for transient modelling

Due to the large numbers of wells and recharge combinations, much of the focus of this research was on building and calibrating the steady state model. Developing the ability to run simple transient simulations to test if the model is structurally capable of this was also an objective. The intent of this objective was as a proof of concept, rather than matching transient simulations with observations. To test the capability of the model, a simple transient scenario was carried out.

Transient data can be used for many of the model inputs, as such the complexity of the model can be increased significantly. Simplified transient runs have been tested with differing river flows to see if the model was capable of simulating flow timeseries under varying conditions. The transient testing was carried out using average pumping rates and recharge. The transient model was run with a daily stress period for the year 1/7/2018 to 30/6/2019.

To test the ability to simulate rapid wetting and drying of river reaches, the stream bed conductance of the Selwyn River was increased beyond the rates used in the steady state modelling. This was done to accentuate the losses and gains and increase the speed at which these changes occur. To use the model for transient scenario assessment, a transient calibration would be needed. This parameter change would account for the timing of physical processes, which are not captured fully in a steady state calibration. Completing a transient calibration would require additional input data processing and would increase model run times and therefore require a much longer calibration time.

4 Results

4.1 Trend analysis results

Annual mean flow trend analysis results for the two flow recorder sites on the Selwyn River are shown in Table 4.1. This shows that neither the site at Whitecliffs nor Coes Ford is showing a significant trend, with a p value of less than 0.05. The Sen slopes from this analysis are all negative, which would indicate a declining trend, if significant. The analysis for the full length of record at Whitecliffs resulted in a similar Sen slope to the shorter record chosen to align with data availability at Coes Ford.

Table 4.1 Trend analysis results for mean annual flows in the Selwyn River.

Site	P value	Sen slope
Selwyn River at Whitecliffs (1984-2019)	0.539	-0.01
Selwyn River at Whitecliffs (full record)	0.175	-0.01
Selwyn River at Coes Ford	0.209	-0.018

As described in section 2.3.1.1 and shown in Figure 2.3, the low flows at Coes Ford have been declining over time but those at Whitecliffs have not. Table 4.2 quantifies these findings and indicates that the 7-day Annual Low Flow (ALF) has a statistically significant declining trend at Coes Ford. This Sen slope from this analysis indicates that the 7-day ALF at Coes Ford has been declining at an average rate of 14L/s per year. The flow at Whitecliffs has not shown any significant decline over this same period.

Table 4.2 Trend analysis results for 7-day ALF in the Selwyn River

Site	P value	Sen slope
Selwyn River at Whitecliffs (1984-2019)	0.224	-0.003
Selwyn River at Whitecliffs (full record)	0.1	-0.002
Selwyn River at Coes Ford	0.003	-0.014

Analysis of monthly data provided further confirmation that the summertime flows in the Lower Selwyn River at Coes Ford have been declining. The monthly trend analysis shown in Table A.2 and Table A.3 (in Appendix 3) indicates that there are significant declining trends in the average monthly flows for December, January, February, March and April. These tables include other lowland streams and the surrounding alpine rivers. The only other significant monthly trends were found for the Waimakariri River July flows, which show an increasing trend and the Rakaia River February flows which show a decreasing trend. None of the other lowland streams showed similar trends to those seen at Coes Ford.

Analysis of rainfall sites operated by Environment Canterbury resulted in no significant trends being found in the annual rainfall totals. These findings are shown in Table 4.3. Similar results were found when monthly analysis was carried out for these rainfall sites. Table A.4 and Table A.5 in Appendix 3 show that the only site with a significant trend is Ridgens Road, which shows an increasing trend in October rainfall totals.

Table 4.3 trend analysis results of annual rainfall

Site	P value	Sen slope
Selwyn River at Whitecliffs	0.546	2.151
13 Mile Bush	0.546	1.477
High Peak	0.854	-0.27
Ridgens Rd	0.76	-0.929
Halswell River at Ryan's Bridge	0.338	4.923
Taumutu	0.511	6.5

4.2 Modelling results

The grid based numeric MODFLOW model can produce a very large array of results. Each model cell has resulting water levels and fluxes for each scenario and model timestep. It is not possible to present all these results in this thesis, so a selection of the relevant results is included in this section and discussed further. While the model contains five vertical numeric layers, only the resulting water levels for the top layer are mapped and described further, as these are most relevant to the interactions with the Selwyn River. As there was little information on discharge directly through the bed of Te Waihora when this model was developed, this discharge and the offshore discharge have been reported together to acknowledge the uncertainty associated with the path of water under the lake. Table 4.4 shows the simple water balance resulting from the baseline steady state model.

Table 4.4 Steady state water balance from the baseline calibration scenario

Component	Inflow to model (m^3/day)	Outflow from model (m^3/day)
Recharge	1,161,241	
Water abstraction		-1,355,423
Drain flows		-1,033,538
Alpine river recharge	1,212,438	-299
Selwyn and Irwell rivers	264,691	-89,879
Discharge to Te Waihora and offshore		-159,235

4.2.1 Calibration match to observed values

Simulating flows in lowland streams is one part of this research; many of these streams have been simulated using the Drain Package in MODFLOW. While fully matching flow dynamics in all these streams is not the primary objective, it is important that the modelled flows are close to observed flows. Figure 4.1 shows the flows for drains simulated by the model compared to the observed flow and flow targets based on recorded data and Clark (2014). The Otukaikino River is located very near to the model boundary and is influenced by flows in the Waimakariri River. These interactions are not captured fully by the model and as such the simulated flows in the Otukaikino River are much lower than those that are observed. There is limited recorded flow information for the Waikekewai Creek, so only the simulated flows are plotted.

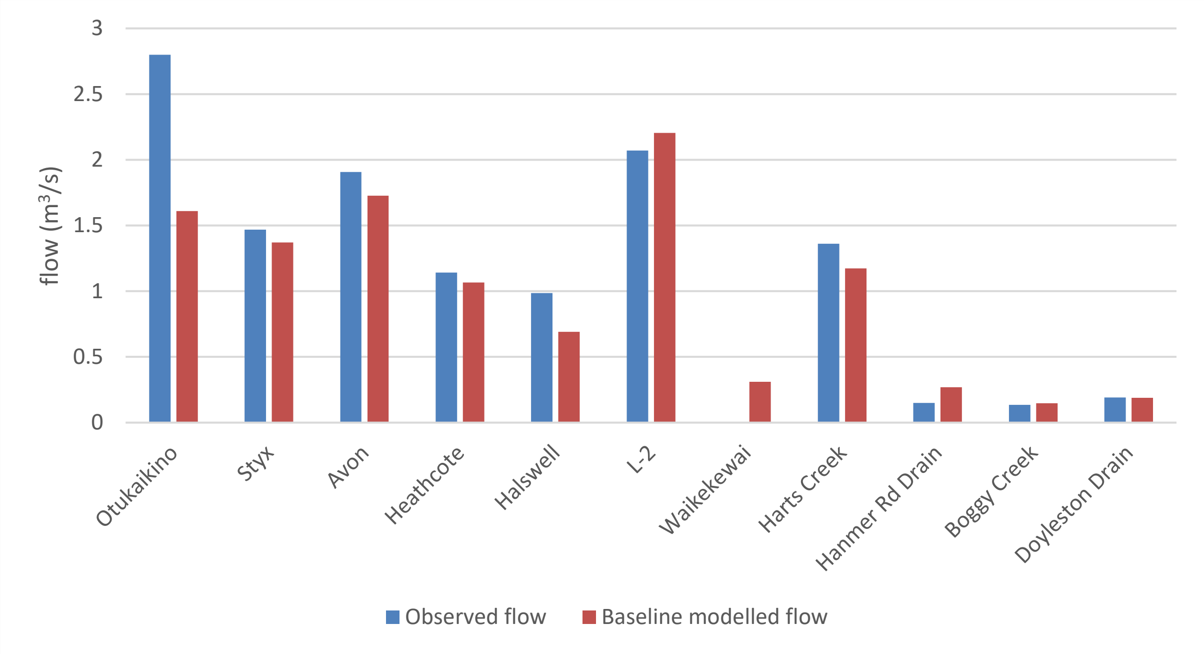

Figure 4.1 Simulated drain flows compared to observed flows for the modelled period.

Groundwater levels were also calibration targets, and Figure 4.2 and Figure 4.3 show how the simulated heads match with observations from both the groundwater level recorders and the manual level measurements. A perfect model fit would result in all simulation and observation pair plotting on the red one-to-one line. Both plots indicate a generally good agreement between the model and observations. There are, however, a small number of recorder locations where the model is under-predicting groundwater levels, compared to observations. This underprediction does not occur when comparing the modelled head to the manually recorded groundwater levels.

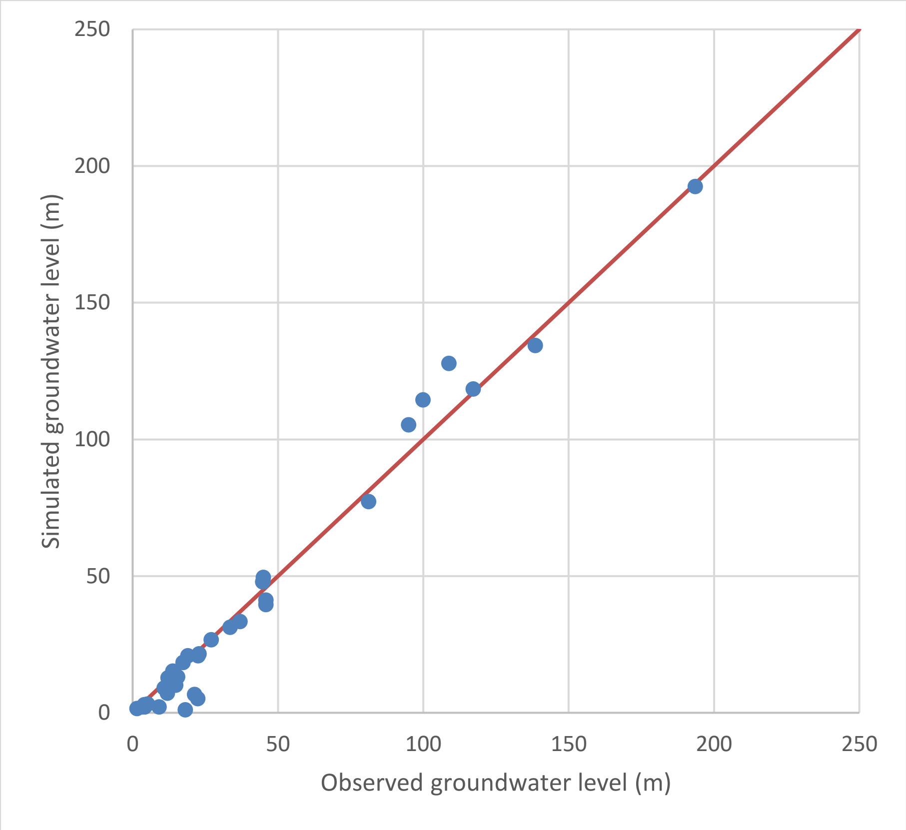

Figure 4.2 Simulated groundwater levels compared to observed levels at recorder locations.

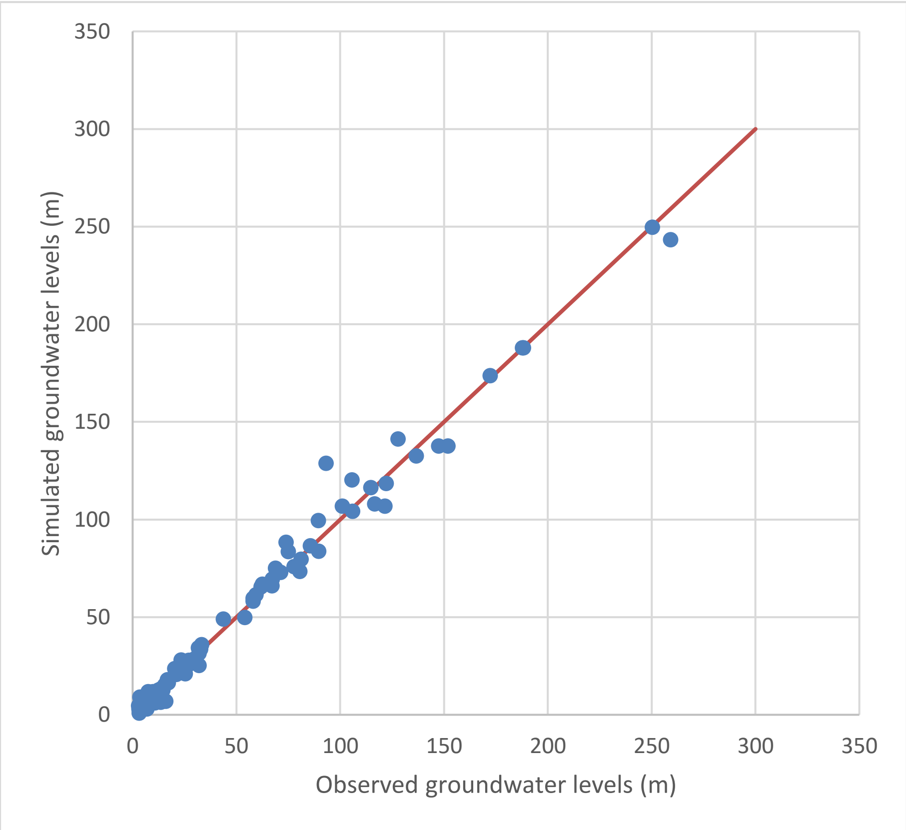

Figure 4.3 Simulated groundwater levels compared to observed levels at manual measurement sites.

4.2.2 Scenario testing

A key objective of this research was to be able to carry out scenario testing to simulate what might occur under conditions which are different to those that have been observed. Eight scenarios have been modelled to test a range of possible changes which could occur in the Selwyn/Te Waihora Catchment. These scenarios were each run using the steady state model to simulate the long-term average effects on groundwater levels and surface water flows. The scenarios modelled are summarised in Table 4.5. These scenarios cover a range of possible changes to climatic input and human interventions such as abstraction and water races.

Table 4.5 Descriptions of steady state scenarios modelled.

Scenario	**Description**
Baseline	This scenario is what all other scenarios are compared against. Recharge and abstraction are representative of conditions currently occurring. Recharge includes the current water race network losses. The abstraction in this scenario has been modelled to be occurring at 50% of the maximum allowable rate.
No water race recharge	Current levels of abstraction. Recharge due to losses from the water races have been removed. This represents the races being lined or no longer operating.
Increased recharge	Current levels of abstractions. 10% increase in recharge, includes current water race losses. This scenario represents an increased recharge rate due to wetter climatic conditions.
Decreased recharge	Current levels of abstractions. 10% decrease in recharge, includes current water race losses. This scenario represents a decreased recharge rate due to drier climatic conditions.
Increased abstraction	Increased abstraction rates of all wells by 10% compared to baseline. Current recharge rates, includes current water race losses. This scenario represents a small increase in abstraction under the current climate conditions.
Decreased abstraction	Decreased abstraction rates of all wells by 10% compared to baseline. Current recharge rates, includes current water race losses. This scenario represents a small decrease in abstraction under the current climate conditions.
25% increase in abstraction	Increased abstraction rates of all wells by 25% compared to baseline. Current recharge rates, includes current water race losses. This scenario represents a moderate increase in abstraction under the current climate conditions.
No abstraction	No abstraction occurring from within the catchment. Current recharge rates, includes current water race losses. This scenario represents what may occur if all current abstraction was replaced by water supplied from out of the catchment.

Each of the scenarios resulted in a set of model outputs including groundwater levels and flows. Figure 4.4 shows the simulated head for the cells in layer 1 of the model for the baseline scenario. Layer 1 is being reported here as it has the most influence on the flows in the Selwyn River. The baseline scenario is what all the following scenarios are compared against. This allows the focus to be on the changes between the scenarios rather than the absolute values being reported in each.

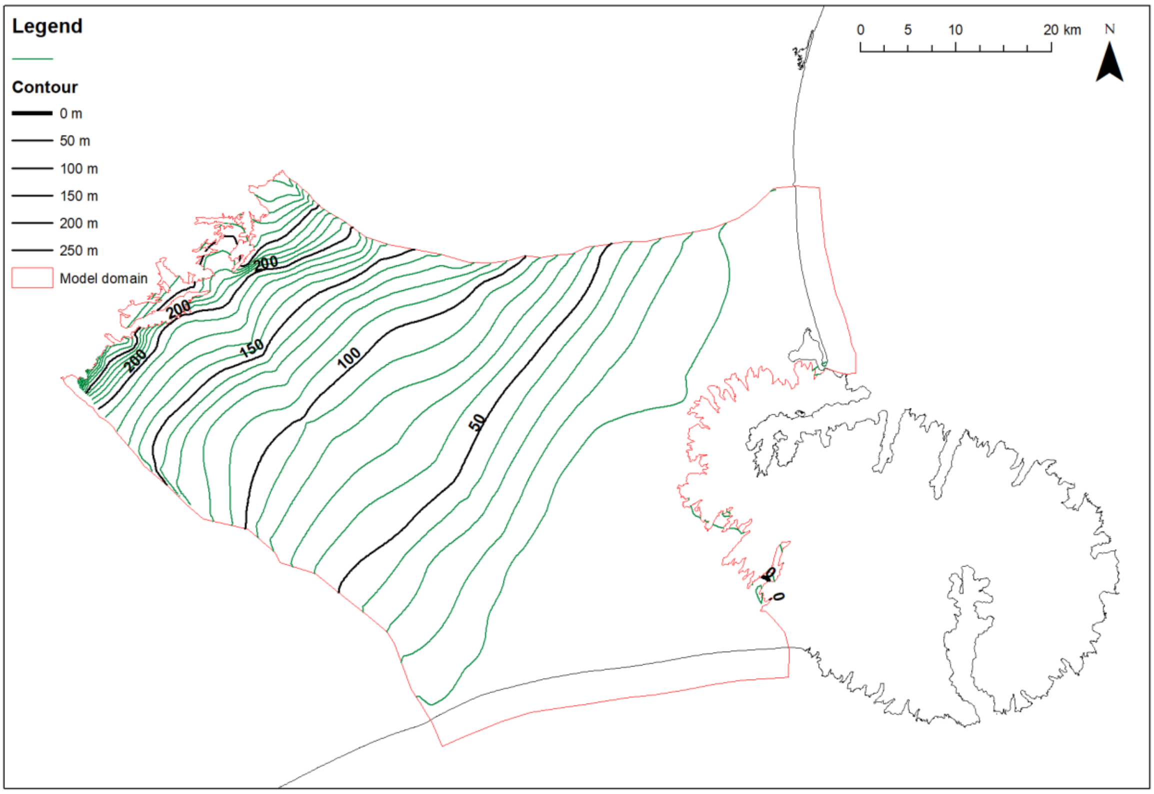

Figure 4.4 Baseline scenario head elevations in layer 1

Figure 4.5 shows the change between the baseline scenario and what is modelled to occur if the additional recharge from the water race networks no longer occurred. This results in a lowering of groundwater levels across the model domain, with the most extreme changes occurring in the upper plains where a decrease of more than 5m in groundwater level is predicted by the model.

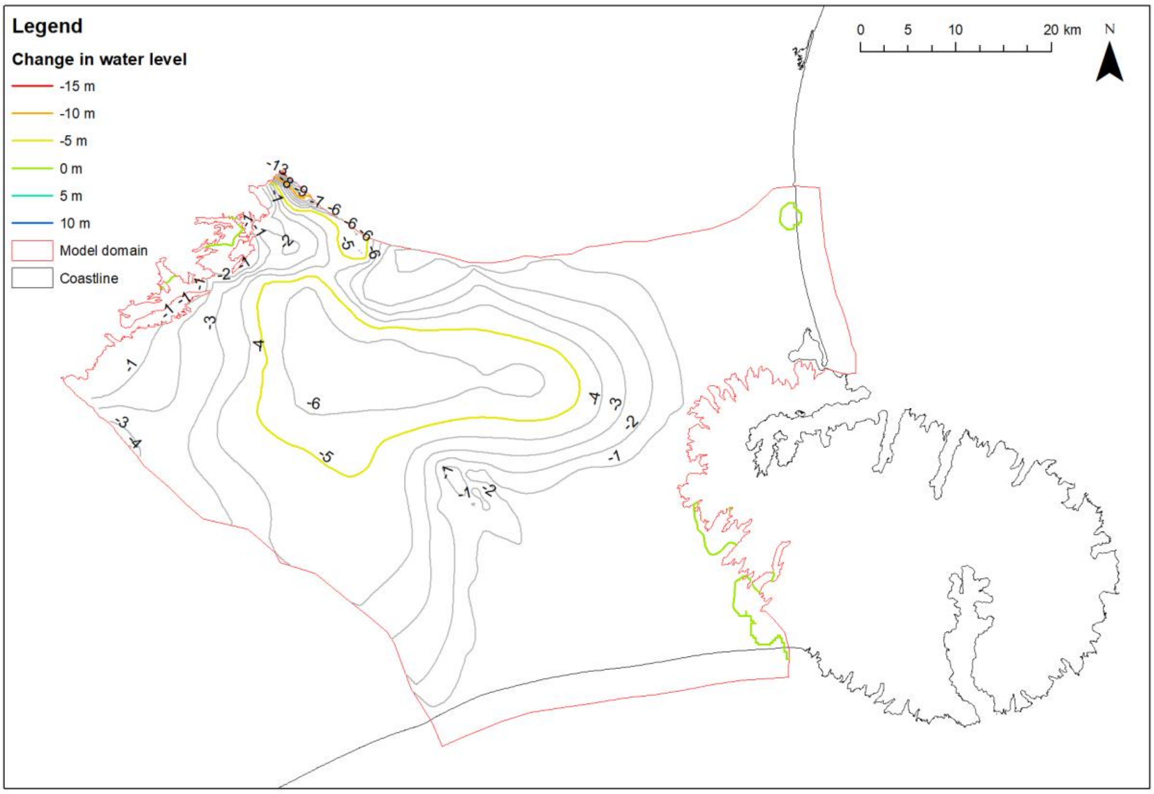

Figure 4.5 Change in layer 1 head elevation from baseline to the no water race recharge scenario.

Comparing the increased recharge scenario to the baseline results in the changes in groundwater level shown in Figure 4.6. This results in an increase to groundwater level across the model domain, with the greatest changes occurring on the light inland soils which currently have high recharge. As recharge was increased by 10% across the model domain, this area would have the largest increase in recharge depth.

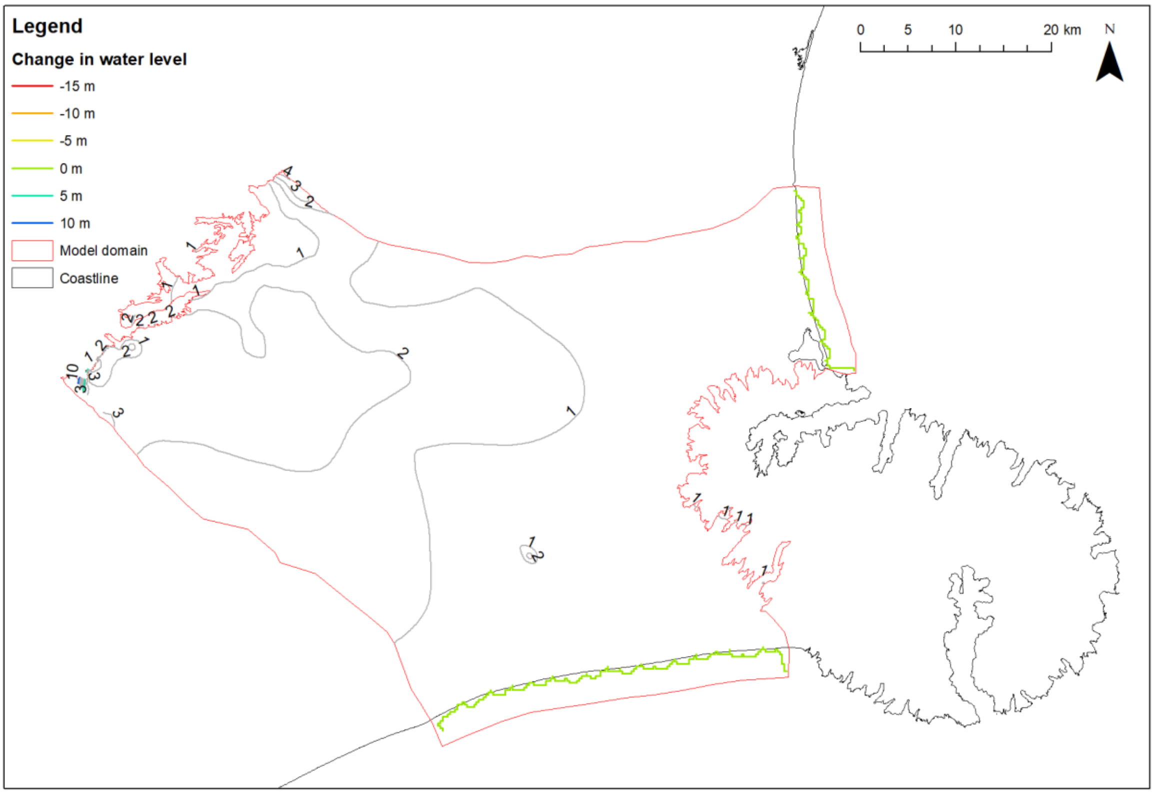

Figure 4.6 Change in layer 1 head elevation from baseline to the increased recharge scenario.

Decreasing the recharge across the model domain resulted in a change for the baseline head elevations shown in Figure 4.7.This shows the opposite effect to the increased recharge scenario, but the largest changes are occurring in the same areas. This simulates what may occur under a drier climate.

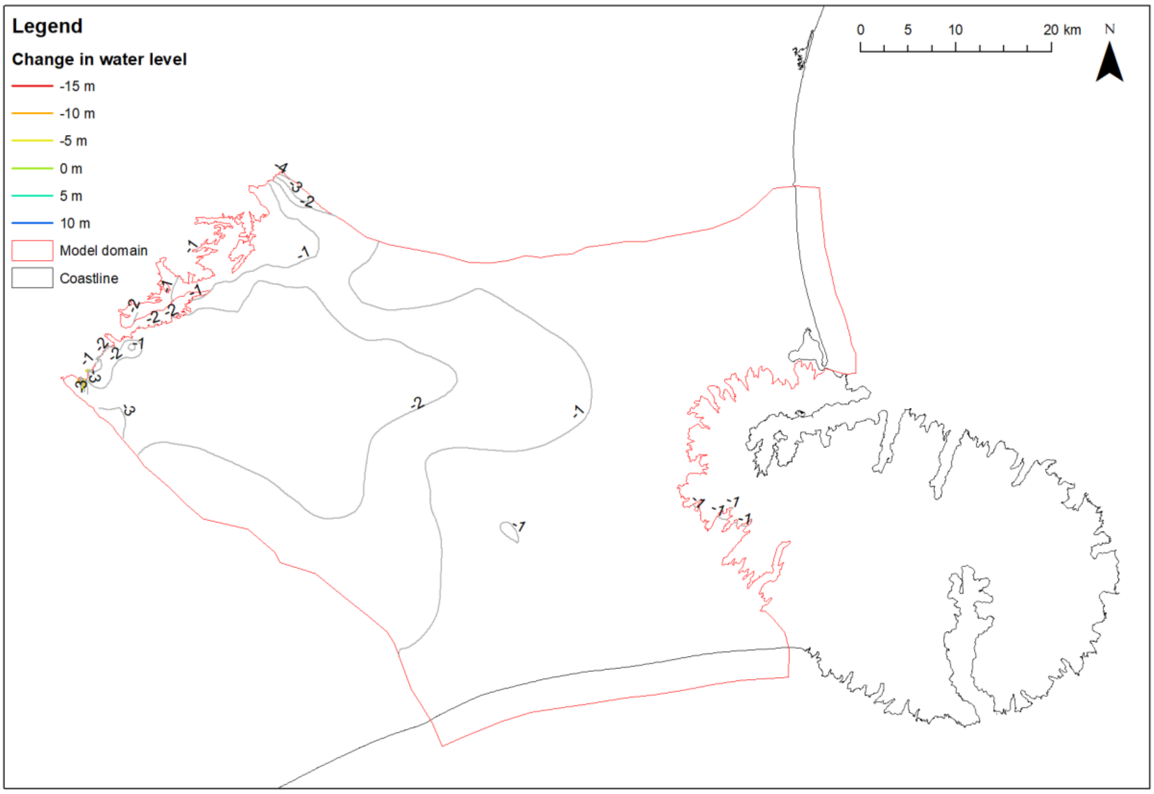

Figure 4.7 Change in layer 1 head elevation from baseline to the decreased recharge scenario.

Simulating an increased usage of water by increasing abstraction from wells by 10% resulted in little change near the coast but up to 2m decrease in groundwater levels in the mid to upper plains. The distribution of the changes in groundwater level is shown in Figure 4.8. This highlights that cumulative changes in abstraction may result in changes to groundwater over a wide and variable area.

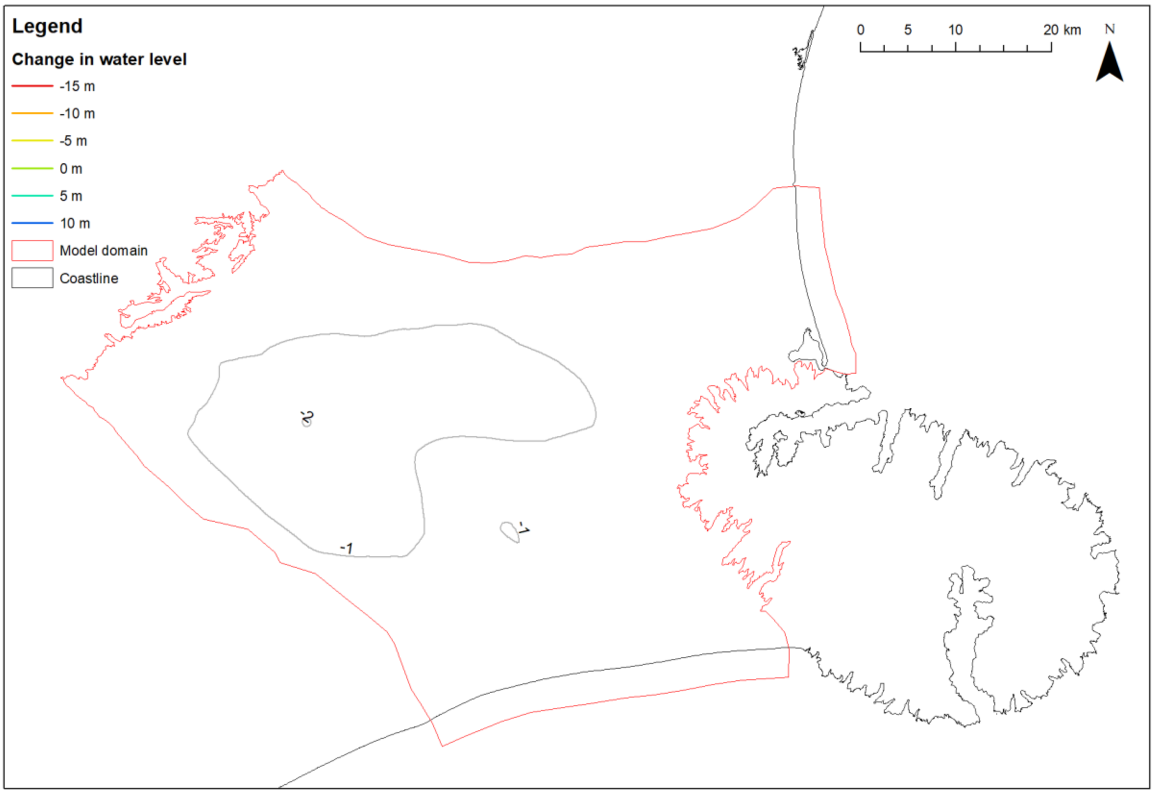

Figure 4.8 Change in layer 1 head elevation from baseline to the increased abstraction scenario.

Simulating a 10% decrease in groundwater abstractions resulted in the change in groundwater level shown in Figure 4.8. This shows an opposite effect to the scenario with increased abstraction, but the area with the largest change extends further south towards the Rakaia River. This scenario also showed little change near the coast and the area adjacent to the Waimakariri River.

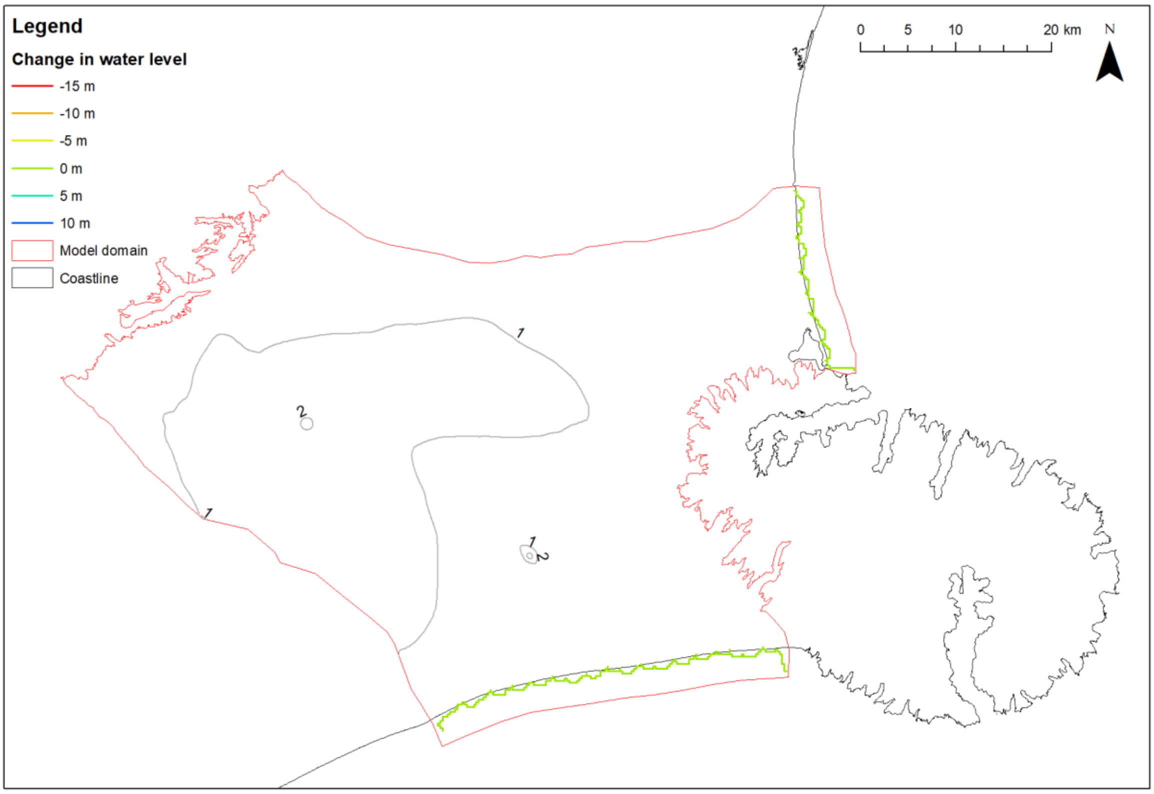

Figure 4.9 Change in layer 1 head elevation from baseline to the decreased abstraction scenario.

Increasing the abstraction by 25% compared to the baseline resulted in declining inland groundwater levels by 5m, as shown in Figure 4.10. The change near the coast was again very small. But the decreased groundwater levels extend further down the plains than under the scenario where abstraction was increased by 10%.

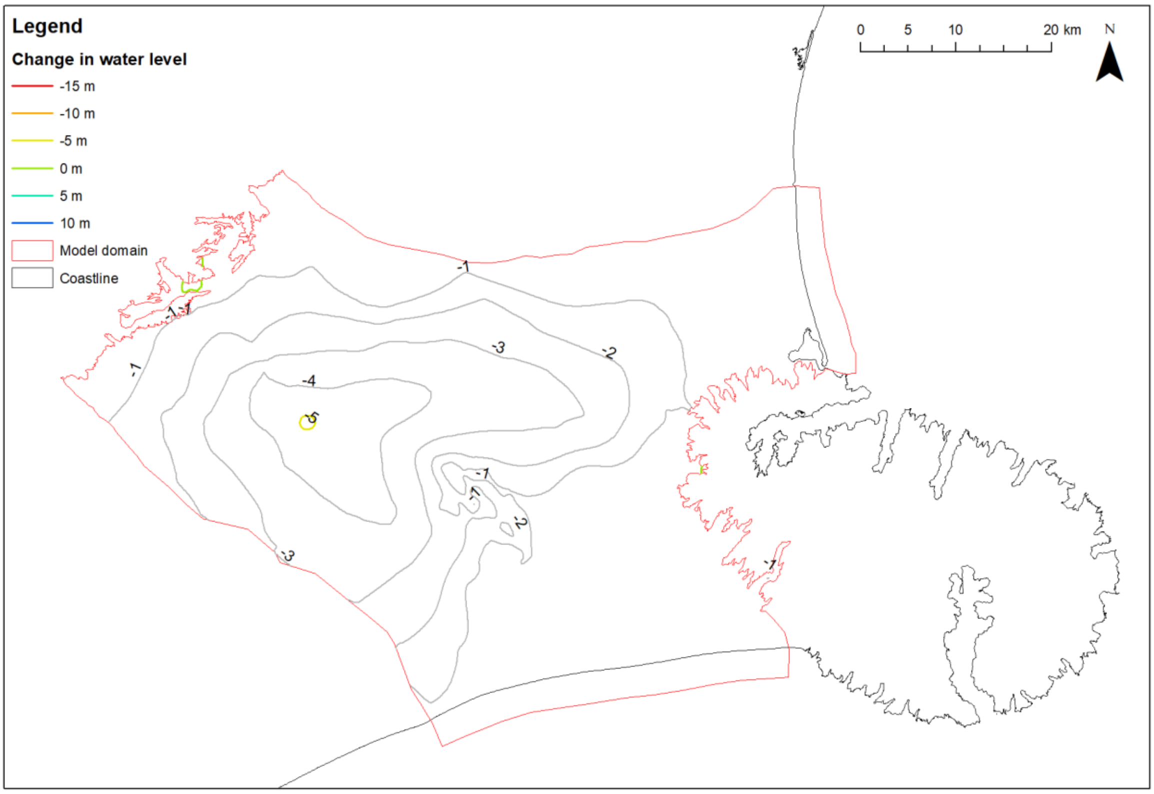

Figure 4.10 Change in layer 1 head elevation from baseline to 25% increase in abstraction scenario.

Simulating a scenario where no abstraction is occurring from the groundwater system within the model domain resulted in the changes in groundwater levels shown in Figure 4.11. This shows an increase in groundwater levels across most of the model domain, with some large increases in the light soils of the inland plains. As this scenario still has recharge including contributions from irrigation, the area with the largest charge corresponds with areas with high recharge which are currently irrigated from locally-sourced groundwater. Under this scenario, much of the plains could experience 5m or more increase in groundwater level, with up to 15m increases in some areas.

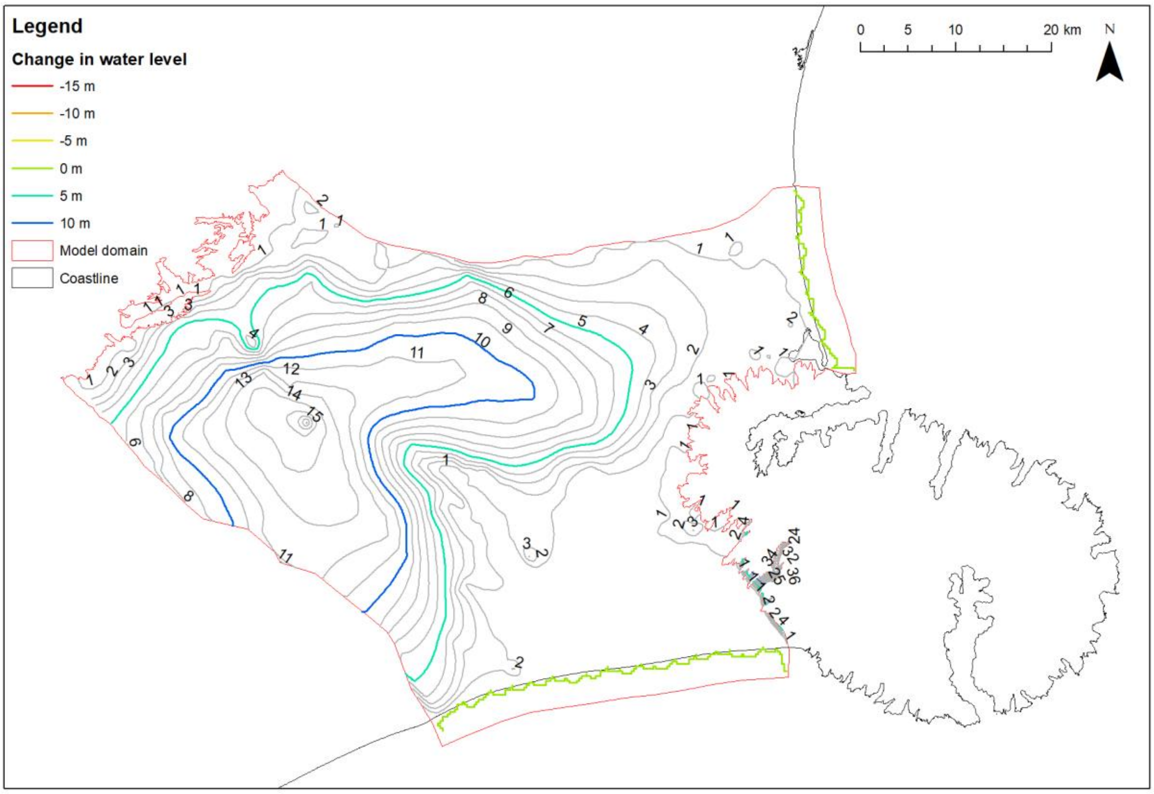

Figure 4.11 Change in layer 1 head elevation from baseline to no abstraction scenario.

Each scenario also resulted in the ability to map stream flow across the model domain. Figure 4.12 shows the SRF2 cells modelled to have surface flow in the baseline scenario. This map also gives an indication of the magnitude of flows, the focus of this being on low flows. As can be seen from this, under the steady state baseline the Selwyn River is simulated to flow along its full length under mean flow conditions. However, the tributaries of the Selwyn River and the Irwell River have reaches with no flow. This indicates that the model is capable of simulating the dry reaches even if these do not appear in the mainstem under steady state conditions. The other scenarios all show changes to the wetting and drying of the tributaries and Irwell River. These other scenarios result in changing flows in the Selwyn River but do not result in dry reaches of the mainstem under steady state conditions. For this reason, stream flow maps for the remaining scenarios are included in Appendix 4.

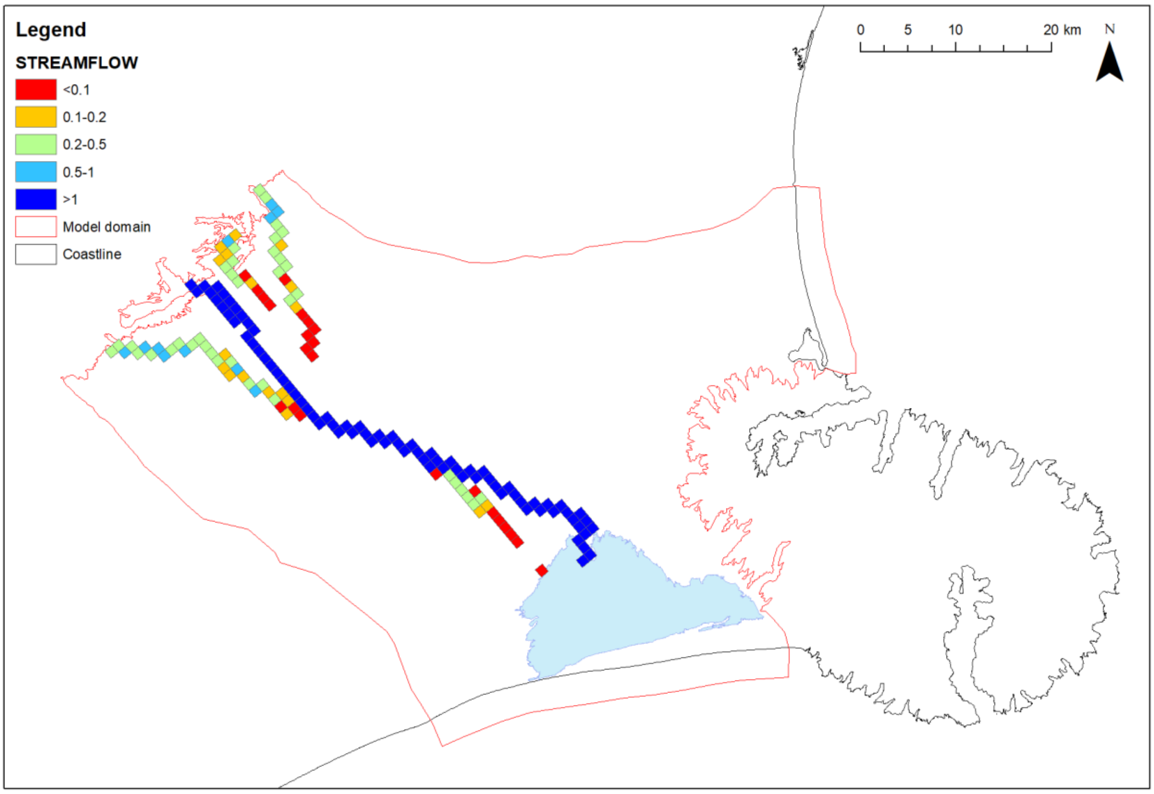

Figure 4.12 Baseline scenario SRF2 stream flow

4.2.3 Transient stream flow modelling

The transient modelling completed as part of this thesis was carried out to test if the model was structurally capable of producing a daily time series of flow for different locations on the Selwyn River. Simulating flows for the hydrological year 1 July 2018 to 30 June 2019 was carried out as described in section 3.7. This test scenario included a combination of daily flow inputs and averaged recharge and abstraction; using these, a timeseries of flow was able to be generated for each model cell that included a SFR2 reach.

The stream bed conductance resulting from the steady state calibrations resulted in more permanent flows down the length of the river than is currently observed. In the transient test scenario, the stream bed conductance in the mid Selwyn River was increased to result in more realistic drying of the SFR2 reaches. This is described further in section 5.

Using this transient testing scenario, the example hydrograph in Figure 4.13 was produced for the Selwyn River at the Hawkins River confluence. This site is shown as it is an example of where the model predicts that the river is dry for much of the year and flows only occur when flows from the foothills are high. The transient flows have not been calibrated so the absolute values may not match observed flows. However, the scenario shows that the model can produce a time series of flows at any point on the Selwyn River or its tributaries.

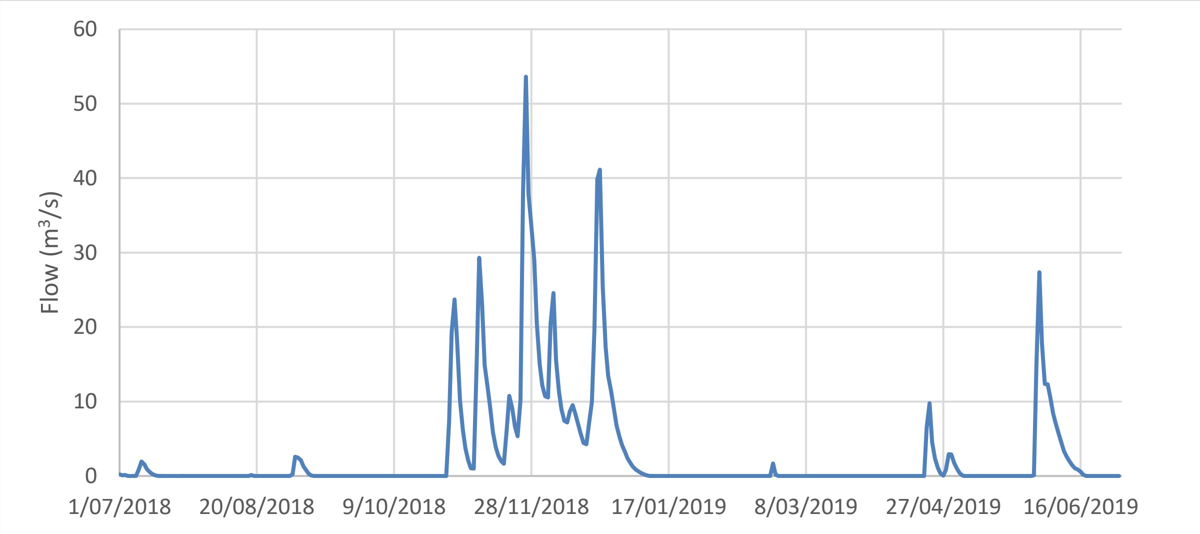

Figure 4.13 Hydrograph for the Selwyn River at the Hawkins River confluence produced from the transient model.

Under transient conditions, maps can be generated for every day that the model is run. An example period of the week from 23/2/2019 to 1/3/2019 has been chosen to plot as this shows disconnection in the Selwyn River mainstem at the start of the period, and then a fresh flow coming down the river causing it to flow for its full length and then dry again within the weeklong period. Figure 4.14 shows the first day of this example period, where the Selwyn River has a dry middle reach prior to the fresh flow. The maps for the following six days are included in Appendix 5. This transient testing indicates that the model can predict rapid changes in surface flow as well as longer term groundwater-driven changes as shown by the steady state scenario results.

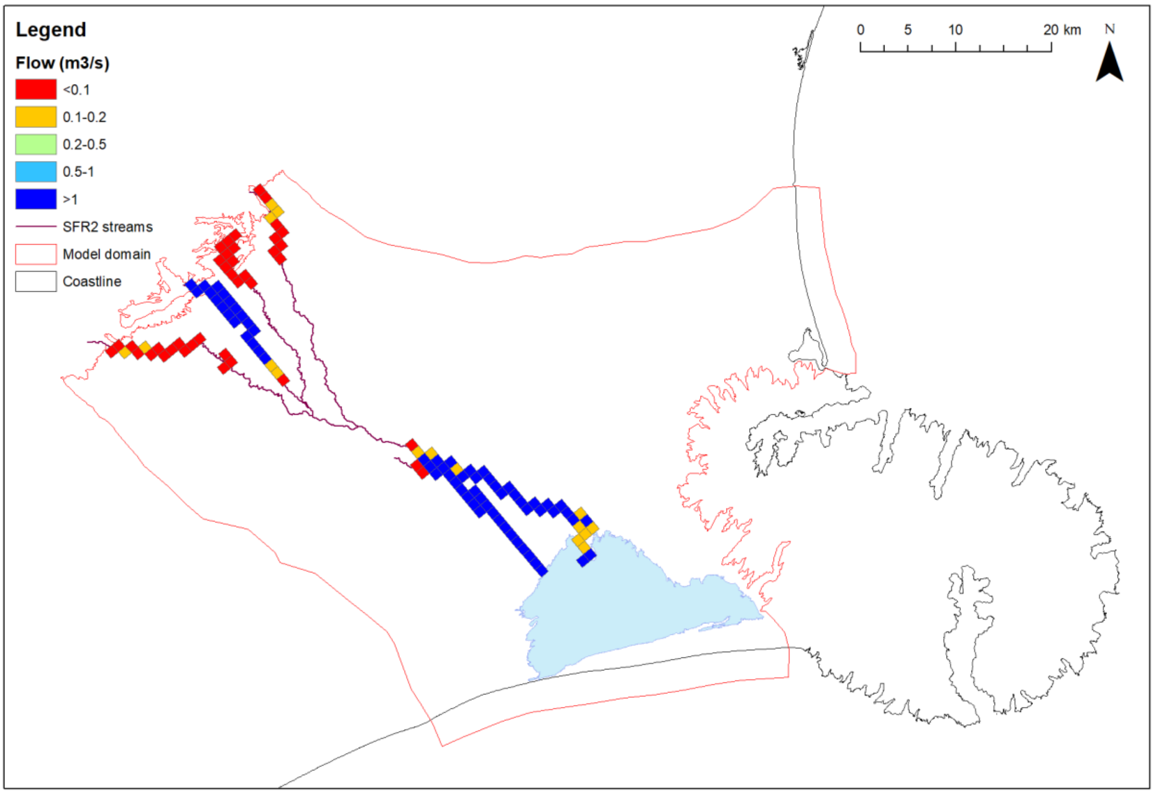

Figure 4.14 Spatial extent of SFR2 cells with surface flow on 23/02/2019

5 Discussion

This study investigated the drivers of flow in the Selwyn River using two different approaches: trend analysis of recorded data, and numeric modelling of the catchment using the MODFLOW code. Combining the findings of the modelling and trend analysis provides two lines of evidence, which indicate that both climatic conditions and groundwater abstraction are contributing to declining flows in the Selwyn River. The trend analysis forms part of the background data processing and helped to develop a conceptual model of the catchment, which ultimately informed the development of the numeric model.

5.1 Trend analysis

Completing a trend analysis on the recorded data within the catchment highlighted that the lower Selwyn River flows are declining in the summer months. Flows for neighbouring lowland streams and alpine rivers were also analysed and reported in section 4.1. Flows in other lowland streams around Te Waihora and Christchurch City are not showing the same declining trend as the Selwyn River. Flows in the alpine rivers on either side of the Selwyn River are also not showing the same trend as the lower Selwyn River. The flows leaving the foothills at Whitecliffs are not declining. This indicates that the changes seen in the lower Selwyn River are likely being driven by changes in groundwater within the plains, and that the streams nearer the alpine rivers may be remaining stable due to the river recharge providing a larger influence on their flows.

The rainfall measured across the catchment is not showing trends in monthly or annual totals. The only rainfall site with a statistically significant trend is the October rainfall at Ridgens Rd, which shows a slight increasing trend. The other recharge component that would ideally be included in the trend analysis is evapotranspiration, however the climate station at Lincoln has been moved multiple times since it began operating and it appeared that this resulted in step changes in potential evapotranspiration, which would impact the trend analysis. However, based on the trend analysis able to be completed, the summer flows in the Selwyn River are declining over a period that coincides with increasing groundwater allocation and abstraction, while rainfall and surrounding stream flows are not showing any trends.

These findings indicate that climate drives the year-to-year flow variability in the lower Selwyn River and the lowest recorded flows have occurred following multiple low rainfall/recharge years. The declining trend seen across the length of the recorded flows is overlaid on the year-to-year variability, resulting in the dry years having lower flows than would occur naturally.

5.2 Modelling

Modelling was a major focus of this study and while a regional scale model was produced, the scope of its intended use was a key factor in many of the decisions and assumptions in its development. In this chapter the rationale and implications of these decisions are discussed, highlighting how these may influence the findings and suggesting possible refinements if the model were to be applied for other purposes. It must be highlighted that the model was focused on the interactions between the Selwyn River and surrounding groundwater, and that while there are many other areas where the model can make predictions, these were not where most of the effort was spent. For this reason, if the model is to be used for other purposes, further refinement and calibration will likely be required.

Throughout the model development there have been many decisions on the balance between model detail, development effort and certainty of predictions. As this study was set out to develop the model using tools available to most practitioners, this limited the level of detail which could feasibly be captured within the modelling. By building a model which runs and is calibrated on a standard laptop, computational resource requirement and model run time influenced many of the decisions around the level of detail to be incorporated into the model. If this study utilised high performance computing, more numeric complexity could be included, however the limitations around observation data for model calibration would remain.

5.2.1 Representation of geology within the MODFLOW model

The MODFLOW model requires a representation of geology and associated hydraulic properties; this can range from a simple one-layer model with uniform properties, to a many-layered model with many horizontal and vertical zones representing different geological features. In this study a range of different ways of representing geology were investigated and tested. This was an iterative process and followed a parsimonious approach of only adding further detail if it resulted in an improved model.

Initially the many bore logs were extracted from the Environment Canterbury wells database and the strata observations were simplified down to 5 classes. These bore logs were imported into the GMS software and the stratigraphy tools were used to create a 3D geological model. Due to the vast number of bore logs and subjective nature of reclassifying strata into a small number of categories, this resulted in representations of geology which did not align with the conceptual model of the catchment or existing geological studies within the model domain (Begg et al., 2015; Vincent, 2005).

Abandoning using the bore logs to define the geology led to a simple five layer model being developed with evenly spaced vertical layers between the land surface and the basement defined by Jongens (2011). This model was run and tested using one set of hydraulic properties for each layer. This was found to capture surface water- groundwater interactions and match some groundwater levels but not to a degree that was considered suitable for this study. From this five layer model a 15-layer model was developed based on the geological layers defined by Begg et al. (2015). Each geological layer was represented as two numeric layers. This 15-layer model was run with a single set of hydraulic properties per layer. This iteration of the model took much longer to run than the five-layer model without major improvements in the fit of simulated and observed groundwater levels; the thinner layers also resulted in some instability in the model in areas where multiple layers had cells which dried.

The final iteration of the model reverted back to a five-layer model, but with different thickness layers based on the Begg et al. (2015) geological model layers. Each of the layers' hydraulic conductivities were assigned using an automated parameter estimation with single values per layer; this was then set as the initial value for each of the pilot points and further automated parameter estimation was carried out. Using the pilot points to define hydraulic conductivity removed the need to define different geological zones, as would be required if a bulk conductivity were assigned. This automated parameter estimation was also used to estimate the vertical anisotropy, which was very high for some parts of the model, up to 1:100. This indicates that there is much more lateral water movement through the groundwater system and that water percolates very slowly into the deep aquifers. This may reflect an averaging of properties of the geology laid down by fluvial processes as the Rakaia and Waimakariri Rivers deposited gravels to form the Canterbury Plains. If the gravels of the Plains have a braided nature with preferential horizontal flow paths and layering of fine materials interlaid with the gravels, this would explain the high vertical anisotropy values predicted by the model.

5.2.2 Simulation of Te Waihora and coastal discharge

As described in section 3.5.6.3, Te Waihora has been included in the model as a general head boundary applied to the cells in the top model layer in the area the lake covers. This general head boundary had a constant head level, however the water level in Te Waihora can vary greatly across the year depending on the lake openings. As the lower parts of the Selwyn/Te Waihora Catchment (and therefore model domain) has a low gradient, the water level within Te Waihora acts as a control for groundwater levels and stream flows in the lower catchment. If the lake level is lower there is a larger gradient in the streams and velocity increases, resulting in a lower water level for a given flow. As the lake level rises the water levels in streams increase and velocity decreases. These interactions have not been captured within either the steady state model or the transient model. If the effects of lake management were to be simulated using the MODFLOW model, the Lake Package could be used, or if a simpler approach is preferred a time varying head could be applied over the general head cells.

As Te Waihora is at the bottom of the catchment it is the receiving body for surface water flows and also some groundwater discharges through the lake bed (Ettema & Moore, 1995). The seepage through the lakebed was determined by adjusting the conductance parameter for the general head cells; this conductance was a calibration parameter, with the estimates of seepage from Ettema & Moore (1995) used as the initial values. The calibration resulted in a lower conductance than that of Ettema & Moore (1995).

Not all the groundwater reaching the lower part of the catchment discharges to streams or Te Waihora; an unknown amount discharges offshore. For the purposes of this study this unknown discharge can be considered as the residual of the water balance, as the conductance for offshore was set at a level to provide unimpeded discharge. This assumption around offshore discharge is likely to impact on the discharge emerging into Te Waihora as water would more easily flow offshore than emerge in the lake. As there were no groundwater levels within the lakebed or large-scale seepage values to use for calibration targets, the lake seepage was uncertain. However, following the development of the model, recent publications by Coluccio et al. (2020) and Coluccio et al. (2021) have provided further detail into seepage through the lakebed. This recent research could be incorporated in future model revisions and could be used to constrain lakebed conductance calibration. As the focus of this study was to investigate and simulate the drying reach of the Selwyn River, distinguishing whether groundwater emerges through the lakebed or offshore is not within the scope of this study as both discharges would likely have similar implications on flow further up the catchment.

5.2.3 Water use assumptions

Abstraction is a significant part of the water balance, and within the Selwyn/Te Waihora Catchment there are both many abstractions and a large cumulative volume of water authorised to be abstracted. For many years, these abstractions could take water without being required to report on how much of the consented allocation was being used. As water metering data were not used within the model, the steady state model included the assumption that abstractors used 50% of their allowable daily volume. While this aligns with previous studies (Rajanayaka et al., 2009; Sanders, 1997, 2003) and water use on a large scale, it does not capture the variation in water usage in different seasons or within a single irrigation season. Total abstracted volume will likely vary year-by-year depending on weather patterns, land management practices and the crops being irrigated. There will also likely be variation in the day-to-day abstraction based on weather.

In recent years water use data has become available for many takes. This provides a record of the water that was abstracted for consented water abstraction points. Using a timeseries of water use rather than the steady state assumption of 50% usage, could result in an improvement in the transient simulation results. By using the actual abstraction for each well, the day-to-day variation in abstraction would be able to be captured within the model simulations. Using actual water use records within the model would allow the interaction between abstraction points to be captured, for example it may be possible for a single farm to have multiple wells and water use may not be spread uniformly across all wells. Water use records would also allow properties with multiple water sources to be captured more accurately; this would be of particular benefit within the CPW Irrigation scheme area, where irrigators may receive irrigation scheme water and may only retain their groundwater take as a backup supply.

While many abstractions are now metered, there are very few that have full metering records for the full study and simulation period. This means that pre-processing of the water use data would be required to create synthetic usage for the periods when records are not available; a similar process would be required for the abstractions which do not have usable water use records or those which are not metered. Once a suitable timeseries of actual water use is generated the relevant usage can be assigned to each well featured within the model. Due to there being over 3000 wells represented within the model domain, this would be a very large and time-consuming task. This would likely require developing some automated processing scripts to be run, as manually extracting each wells' water use, filling gaps and processing this to be entered into the MODFLOW model would be prohibitively time-consuming. So, while including actual water use records within the model was outside the scope of this study, it may prove to be a valuable future improvement to the model, particularly if tools to process these large data sets become readily available.

5.2.4 Recharge calculations

The recharge used in the modelling was calculated using a spreadsheet soil moisture balance (described in section 3.5.3); this was a very manual process to generate a recharge timeseries for each combination of soil type, climate, and irrigation. Even though there were many recharge combinations, the simplification of the climate data could result in errors in the recharge estimates. As there was only one climate site used to represent the evapotranspiration for the model domain, the variation in recharge may not be fully captured in these estimates. If additional climate sites were available for the period of simulation, these could help provide better spatial variability in the recharge data.

Another option to capture the variability would be to use a gridded climate data set for both rainfall and evapotranspiration, such as the Virtual Climate Station Network (VCSN) created by NIWA (Tait et al., 2006). The VCSN includes daily estimates of rainfall and potential evapotranspiration at approximately a 5km resolution across New Zealand. Using a dataset such as this would provide a better representation of the climate variability within the model domain, compared to the Thiessen polygons used in this study. However, at the time recharge was being calculated for this modelling, the VCSN data did not span the full simulation period. As the updated VCSN data become available a recharge model based on these data could be used to replace the soil moisture balance used in this study; this would also require the model to be recalibrated.

5.2.5 Impacts of the CPW irrigation scheme on recharge

As described in section 2.3, there are parts of the study area where water can now be supplied from the CPW irrigation scheme. This water is sourced from the Waimakariri and Rakaia Rivers, which are not included in detail within this model. This additional water has allowed for some increases in irrigated area and has also provided an alternative to abstracting groundwater. These changes can have impacts on both the recharge and abstraction occurring.

Generating the recharge timeseries used within this study was carried out as described in section 3.5.3. This methodology included the assumption that irrigated areas remained constant throughout the study period. In areas where the addition of water from the CPW irrigation scheme has allowed further areas to be irrigated, there may have been changes in land surface recharge. As the irrigated areas in 2016 were used to represent the whole simulation period, these may be overestimating the area of irrigation early in the simulation period and underestimating areas late in the simulation period.

Including time varying irrigation areas into the recharge calculations would capture the changes in recharge due to the additional area irrigated by the CPW irrigation scheme. However, a time varying spatial data set of irrigated areas for the catchment was not available for inclusion in this study. If this data becomes available and recharge calculations can capture the changes in irrigated area over time, it is expected that the simulated water levels and flows may more closely match observations. This would likely impact both the steady state and transient simulations.

5.2.6 Steady state simulation results

The steady state model developed in this study is considered partially calibrated, rather than a fully calibrated model. The reasoning for this is that while model parameters were adjusted to match simulations with observations, not all the areas of interest have observations. This means that in some of the areas of interest there is no validation of whether the model matches observations or if the parameters are representative of the physical conditions where there are not observations. There are very few observations of flow losses and gains down the length of the Selwyn River within the simulation period, and as this was a desktop analysis, no further field measurements were captured. To estimate the approximate areas of loss and gain, dry riverbed historic observations from outside the simulation period were used. This did not provide a numeric calibration target in the same way that a flow recorder would, but it provided a sense check to make sure that the modelled dry reaches occurred on areas where the river is known to go dry, based on historic records. If this were a longer-term study, concurrent gaugings down the length of the Selwyn River or the installation of temporary flow recorders would provide much better calibration targets. However, this data would be most useful if collected over multiple seasons. This highlights the importance of fully scoping a modelling study and following the process for model application in Figure 3.1 (Bear et al., 1992).

Using the available data and a combination of automated parameter estimation and manual calibration within GMS, the model was able to generally match average groundwater levels at recorder locations and manual measurement locations. Figure 4.2 and Figure 4.3 show how the simulated and observed groundwater levels compare. While most manual measurement locations of groundwater levels were matched quite closely, there were a small number of recorder locations in which the model under-predicted groundwater levels; these were in the 10-20m range. The model was also capable of matching average flows in drains, apart from the Otukaikino River to a satisfactory degree. While using the model to predict changes in these drain flows is not an objective of the model, these drain flows need to match observed flows to ensure a realistic water balance is maintained.

The steady state model was able to simulate which rivers were drying using SFR2 reaches. Figure 4.12 shows the steady state flows for each of the SFR2 cells. This indicates that under steady state conditions the Selwyn and Hororata rivers flow for their entire length and the Irwell, Hawkins and Waianiwaniwa Rivers all have dry reaches. This may differ from what may be seen in the catchment due to the steady state assumptions.

In developing the steady state model, average conditions were used as inputs; this included average recharge, abstraction and flows from the hills. It is unlikely that average conditions for all three of these model inputs are occurring at the same time. As the Selwyn River has highly variable flows across the year, often the times of low flows correspond with low recharge seasons and high abstraction seasons. As the timing and variability of the model inputs are averaged under steady state conditions, the drying reaches of the Selwyn River which occur over summer months are not being represented. This does not mean that the model is not capturing the interactions correctly, but rather highlights the value in the transient modelling which included time varying inflows and was able to simulate dry reaches within the Selwyn River and how these change with differing flows from the foothills.

5.2.7 Simulation of drains

Many of the surface waterways within the model domain have been simulated using the Drain Package within MODFLOW; this was done as a way of simplifying the model and focusing most effort on the Selwyn River. While the Drain Package was simpler than the SFR2 Package, it did allow the inclusion of many drainage features for which there was very little data. Of note are the extensive drainage networks maintained by the regional and district councils, shown in Figure 2.5. These networks have wide coverage in the lower Selwyn/Te Waihora Catchment and areas around Christchurch City.

While the spatial extent of these drains is available and was included in this study, the attributes of individual drains was unknown. Including these waterways as drains allowed them to be included in the model by assuming a uniform depth below the land surface. This resulted in an extensive network of drain cells in the south-east of the model domain. By grouping these together by catchment and receiving body, these were able to be used in the model calibration by adjusting the drain conductance to match simulated outflows with observed flows.

In the areas around Te Waihora and Christchurch City, the extensive drainage networks play an important role of keeping land from being flooded from groundwater. Within the model these drains played a similar role. As the model parameters were adjusted to match both drain flows and groundwater levels, the spatial coverage of drain cells was important to ensure that an appropriate amount of water was routed to drains across a wide area. If a sparser drainage network were used to define drains, there may have been a poorer fit between shallow groundwater levels as a higher drain conductance value would have been required to match drain flows as there would be fewer contributing cells. This would likely mean that groundwater levels near to the sparse network of drains would be lower and groundwater levels further from the network would be higher.

While most of the simulated flows in the drains were similar to the observed flows under the steady state simulation (Figure 4.1), the observed flows in the Otukaikino River were unable to be matched by the model. This may be due to the proximity of the Otukaikino River to the Waimakariri River and model boundary. This inability of the model to match flows may be due to preferential flow paths existing between the Waimakariri and Otukaikino Rivers, which likely exist due to the Otukaikino River being a spring-fed stream which flows in a historic braid of the Waimakariri River.

As the interactions between the Waimakariri and Otukaikino rivers was not a focus of this study, the mismatch between simulated and observed flows was not investigated further. A high drain conductance was applied to the Otukaikino River to match nearby groundwater levels, but this still resulted in an underestimation of surface flows. As the Otukaikino River is far from the Selwyn River it was considered to be unlikely that spending further effort trying to match this waterbody would result in any significant changes to patterns of losses and gains in the Selwyn River. However, it is noted that while the model includes the streams within Christchurch City, it is not the intent that this model be used for assessing changes to these streams. If the model were to be used for predicting the streams within Christchurch City, further refinement and calibration would likely be required.

Near to the Selwyn River, the L-II River was also simulated as a drain. Due to the size of the model cells, the proximity of the L-II and Selwyn Rivers resulted in there being drain cells adjacent to SRF2 cells; this was considered a risk as the drain depth was at similar levels to the Selwyn River cross section. To mitigate this risk one drain cell was removed from the L--II River to ensure that no drain cells adjoined to a SFR2 cell. This would result in a higher drain conductance being required for the remaining L-II drain cells to match the surface flows as these was a slightly smaller area being drained. This approach was considered to have little effect on the losing and gaining parts of the mid Selwyn River where the focus of the study is, as the part of the Selwyn River next to the L-II River is in the lower permanently flowing reach near Te Waihora.

Another way to mitigate the neighbouring drain and SFR2 cells would be to use smaller model grid cells. If smaller grid cells were used over the whole model domain, this would increase the computational load and increase run times. Using MODFLOW USG (unstructured grid) would allow refinement of model cells in some parts of the model domain while having large grid cells in other areas. MODFLOW USG would allow a refined grid to be used around the rivers and drains and have large grid cells on the plains. Some testing of this approach found that the model which worked with a uniform grid in MODFLOW NWT failed to converge when running in MODFLOW USG.

For this reason, the uniform grid approach was continued with, and a more refined MODFLOW USG model could be developed from the model used in this study, if more detailed simulations of the near river processes are required. The trade-off between progressing the operational MODFLOW NWT model and rebuilding the model in MODFLOW USG would be that other parts of this study's scope may not have been able to be met.

5.2.8 Scenario analysis

Using the steady state model to evaluate the range of scenarios described in Table 4.5 allowed different components of the water balance to be altered to test how this influenced the groundwater levels and flows. The baseline scenario is the scenario which all others are evaluated against. As the model does not match observations perfectly it is important to make comparisons between model scenarios rather than comparing each to the observed values. By comparing between scenarios, the effects of the different scenarios are highlighted rather than the uncertainty of the model. As the model is only partially calibrated, the comparisons between scenarios are most helpful in describing the magnitude and direction of change between scenarios rather than an absolute surface flow rate or groundwater level.

The no water race recharge scenario simulated what would happen if the additional recharge from the water race network no longer occurred. This could occur if the water races were closed or lined to reduce losses. The races contribute a large component of the rechange in the upper plains and the resulting groundwater levels from this scenario showed a large decline in groundwater in the mid to upper plains, with the largest changes occurring in the centre of the model domain where the recharge from the alpine rivers has the least influence. This scenario did not result in a change to drying extent of the Selwyn River but did result in decreased flows and an increased dry reach in the Irwell River. This indicates that the water races help to maintain flows in the Selwyn and Irwell rivers and are likely to be an important recharge contribution, particularly in the summer months when other sources of recharge are reduced.

The increased recharge scenario simulates what may happen if there is a uniform 10% increase in recharge across the model domain. As this is applied uniformly across the model domain rather than a targeted area or land use, it reflects what may occur in wetter climatic conditions. This scenario resulted in increased groundwater levels, with the largest increases occurring on the light soils in the north-west of the model domain. This area already has high recharge, so the 10% increase resulted in a larger absolute depth change than across the rest of the model. This scenario resulted in the Selwyn River continuing to flow for its entire length, and the Irwell River was predicted to flow for its full length. This scenario resulted in a small number of cells, where the Selwyn River reaches Te Waihora, having very large predicted changes in groundwater level. This shows in several scenarios and is an anomaly which may be occurring where the SFR2 stream meets the general head boundary representing Te Waihora. This may be resolved if Te Waihora were included using the Lake Package within MODFLOW, but this would increase model complexity and resource requirement. As these small numbers of cells are unlikely to impact on the drying reaches of the Selwyn River, this has not been investigated further.

The decreased recharge scenario is similar but opposite to the increased recharge scenario and reflects a climatic change in recharge due to either decreased rainfall or increased evapotranspiration. This drier climate is simulated with a uniform 10% decrease in recharge across the model domain. This showed a decline in groundwater levels across much of the plains with the largest changes occurring inland where land surface recharge is high and the largest contributor to the groundwater. Further down the catchment there is less change as this area receives less land surface recharge and is influenced by losses from the alpine rivers and coastal head.

The increased abstraction scenario represents what may happen if all abstractors increased their abstraction by 10% under the current climate conditions. The increased abstraction resulted in decreased groundwater levels and a decrease in flow, with increased drying of the

Irwell River. Due to the distribution of abstractions across the model domain, the changes in groundwater levels vary. The converse effects are seen in the decreased abstraction scenario, which reduced abstraction by 10%. Both changes in abstraction scenarios could occur currently as not all the allocated water is abstracted; a 10% increase or decrease in abstraction could feasibly happen between years. This highlights that the changes simulated in these scenarios may not occur in isolation, for example in a climatically dry year with reduced recharge, abstraction is likely to be higher to mitigate higher evapotranspiration. This means that effects seen will likely be more than either scenario in isolation and the differences between groundwater levels and flows between wet and dry years may be more pronounced.

To further investigate the risk of increasing usage of allocated water, the 25% increase in abstraction scenario was run. This scenario did not go to the extreme of assuming all allocated water was used, but increased usage by 25%. This would be allowable with the currently allocated water allocation limits. However, this resulted in large declines in groundwater across the upper mid plains, where a large amount of the abstraction occurs. This scenario resulted in reduced stream flows and under this scenario the Irwell River has the largest extent of dry reaches. This scenario indicates that there is a large risk that flows and groundwater levels could be reduced further than they are currently if abstractors increase their takes. If all allocated water were to be abstracted it is expected that flows and groundwater levels will decline even further than those predicted in this scenario.

The final scenario tested was a no abstraction scenario. This scenario simulates what may happen if all abstraction ceased. It is not a simulation of the natural state of the catchment as it still contains the additional recharge from irrigated land, water races and the drainage features. What it shows is that if all groundwater abstraction in the catchment ceased and all irrigation was sourced from out-of-catchment supplies via a piped network, groundwater levels would increase greatly. The scenario indicated that groundwater levels in the mid to lower plains would increase to the point where some areas would have surface ponding. This groundwater flooding suggests that if all abstraction ceased and an alternative water source was provided, the drainage network in the lower catchments would not be sufficient to protect all areas from flooding. This scenario showed that the Selwyn River flows would increase as would the flow in the Irwell River. These results are similar to the no abstraction scenario reported in Clark (2014) and Scott & Weir (2014).The interactions between abstraction and drainage are highlighted by the no abstraction scenario and this indicates that increasing river flows by ceasing abstraction may require other interventions. If the recharge were also reduced to that of dryland recharge, the groundwater level changes would be less, but this would require large areas of irrigated land to be reverted back to dryland, which would have implications that are outside the scope of this thesis to investigate.

Testing these scenarios with the steady state model provided insight into the interaction of the different parts of the Selwyn/ Te Waihora water balance and may help with understanding how the catchment could be managed into the future. While none of the scenarios have been intended to represent management options that a regulatory water manager may choose from, they span the range of likely changes which could occur.

5.2.9 Transient modelling

While building a fully calibrated transient model for the catchment was beyond the scope of this study, testing the ability of a simplified transient model was a key objective. The transient model was based on the steady state model and used the same parameters defined in steady state calibration. However, to capture the timing of flow changes, the stream bed conductance for the Selwyn River, below its tributaries, was increased. While these conductance parameters were higher than those achieved through the steady state calibration, they resulted in the ability to replicate the changing flow over time required in a transient model. As the steady state model does not include a change over time the calibration focused on finding parameters which best fitted the average conditions.

As the transient model was developed as a proof of concept to determine if the model structure could simulate daily changes in drying reaches, it was considered appropriate to adjust these parameters. The transient model only had some components which varied over time, rather than all the inputs. This allowed the simple testing and justified a small change to the parameters from those used in the steady state model. By increasing the bed conductance for the mid and lower Selwyn River the model could capture the daily changes in drying reaches. This was not able to be captured in the steady state modelling and only resulted in a small decrease in the model's ability to match groundwater levels.

This transient modelling test was run with one year of data and showed that changes in flows in the upper Selwyn River and tributaries could be simulated as the river crosses the plains, with minimum changes being made to the model. As this transient modelling was only considered to be a proof of concept, transient calibration would need to be completed once transient abstraction and recharge input data were added. While the changes to the stream bed conductance resulted in a better representation of the changes in dry reaches over time, it resulted in a slight decrease in the steady state model's ability to predict average conditions and highlight the need to develop and calibrate models for their specific purpose.

The simplified transient model developed in this study was able to simulate daily changes in flows down the length of the Selwyn River as shown by the figures in Appendix 5. These show the model is capable of producing time series data for flow on any of the SFR2 reaches and if fully calibrated, could be used to test both the temporal and spatial impacts of different water management scenarios.

5.3 Effectiveness of model

Both the steady state and transient models were able to be run to predict changes in flows and groundwater within the Selwyn/Te Waihora Catchment. While neither model is intended to be used to predict absolute flows and water levels, they are both capable of providing insight into the interactions between different parts of the catchment water balance. The steady state model provides an understanding of the spatial extent of changes and the direction of these changes. The transient model provides a temporal representation of how flow moves through the catchment and where the Selwyn River gains and loses flow at different times. If additional field observations of flow at multiple locations down the Selwyn River became available, these models could be calibrated further to better match what is seen in the field and would have more predictive power. Until this time these models provide understanding that can be utilised alongside existing knowledge and data to help inform future studies and field work.

5.4 Uncertainty and multiple lines of evidence

Modelling and model results are subject to uncertainty; this can be due to a range of factors. In this study the uncertainty and limitations of the modelling were identified, and the models have been developed alongside trend analysis to provide multiple lines of evidence on the drivers of flows in the Selwyn River. By using the model to predict size and direction of changes rather than absolute values, some uncertainty is removed in the predictions, as any error associated with the model structure is consistent across scenarios being assessed. The key limitations of the modelling completed are as follows:

Computational processing requirements. The models can be required to run for long periods, particularly when completing automated parameter estimations. The run times increase with the model complexity and number of model cells. Developing the model on a standard laptop with a limited timeframe constrained the model runtimes and calibration runs able to be completed.

Sparsity of river calibration points through period of interest. As this study relied on existing field data, there were few flow observations in the mid reaches of the Selwyn River. This resulted in less ability to calibrate the model to flows in this area and greater uncertainty around predicted flows in the mid Selwyn River. Historic data and conceptual understand were relied on to achieve realistic simulation.

Heterogeneity and model resolution. Due to the large area covered within the model domain, the model grid cells were set at a resolution of 1km x 1km. This was a compromise between the computing requirements (model run times) and the ability to capture variability across the model domain. Within a single grid cell, it is expected that there are a range of different soils and hydraulic conditions. These are aggregated to an average for each cell. This may not capture very localised effects or the heterogeneity within a single model cell. However, many of the required data sets are at a lower resolution than the model grid resolution and this compromise was deemed suitable.

Non-uniqueness of calibration parameters. It is possible to achieve similar calibration results with differing model parameters. The risk of non-unique calibrations is highest when the model has many parameters and few observations to match to. There is a risk in some areas of this model where there are few observed data points that the calibration parameters which achieved the best model fit are non-unique. The uncertainty associated with non-unique calibration can be quantified through a stochastic uncertainty analysis; this however requires running the model many times and relies on a large computing and time resource being available.

Model structure and MODFLOW code. The model code chosen for a model study, along with the application of that code can have limitations and uncertainty. The MODFLOW code used within this study is primarily a groundwater modelling code and has some limitations in how surface water is simulated. As described earlier, surface water features have been included using the River, Drain, or SFR2 features. Each of these has different ways in which surface water and groundwater interact and have different input requirements. Simulating the surface water features using different MODFLOW packages may achieve a similar calibration but result in different flow and groundwater level predictions. For this reason, the most detailed

SFR2 Package was chosen for the Selwyn River to best capture the complex interactions between surface water and groundwater.

Despite these possible limitations, the modelling carried out in this study provides insight into the surface water- groundwater interactions in the Selwyn River and highlights the value of both desktop modelling assessments and field-based campaigns. Neither will be able to provide complete understanding of the surface water- groundwater interaction, but when considered and developed together, they can lead to a fuller understanding of catchment processes.

5.5 Review of research objectives

Through the combination of data analysis and model development the five objectives for this thesis have been achieved as follows:

1. **Develop a conceptual model of the interactions between the Selwyn River and local groundwater.**

This objective was achieved through completing the literature review and processing the observation data within the catchment. This conceptual model formed the basis for the numerical model developed in this study.

2. **Develop a numeric model of the surface water and groundwater systems of the Selwyn River.**

The MODFLOW code was used to develop the numerical model; this was partially calibrated and used to simulate a range of steady state scenarios. The model includes the Selwyn River and surrounding catchments, covering the plains between the Waimakariri and Rakaia rivers

3. **Develop the ability to simulate the effects of changing groundwater level on surface water in the Selwyn River.**

The steady state model was used to test scenarios of changing recharge and groundwater abstraction; these resulted in changes in groundwater, changes in Selwyn River flow and changes in drying reaches in the mainstem and tributaries. These scenarios showed that the model can predict surface water changes resulting from changes to groundwater.

4. **Simulate time series of flows for key locations on the Selwyn River.**

A simplified transient model was developed and tested to show that the model was able to simulate how different reaches of the Selwyn River change in flow over time. This transient model was run with a daily stress period for a one-year simulation and resulted in a timeseries of flow for each of the SFR2 cells modelled.

5. **Use the developed numerical model to simulate the spatial extent of the drying reaches of the Selwyn River under different climatic and abstraction situations.**

The scenarios run using the steady state model captured a range of different recharge and abstraction scenarios; these reflected changes due to climate and abstractors using differing proportions of their allocated volumes. These scenarios resulted in predicted changes in flows, groundwater levels and dry reaches.

5.6 Opportunities for further research

The modelling caried out in this study highlighted a range of areas for future work where this model could be developed further or where additional fieldwork and analysis would be beneficial to future studies:

- Additional flow measurements on the Selwyn River between State Highway One and the confluence with the Hororata River, as this reach is known to dry regularly but has very few flow gaugings.
- Investigate using MODFLOW USG further to allow increased grid cell resolution near to the Selwyn and Irwell Rivers.

- Further develop the transient model to include time varying inputs for all key model components.
- Investigate the use of water metering data collected by consent holders, including extending records and gap filling as an input for abstraction within the model.
- Investigate the use of distributed climate data for calculating daily recharge for input to the model.

6 Conclusion

This research has used a range of methods to investigate surface water-groundwater interaction in the Selwyn River. Using more than one approach provided converging lines of evidence to determine the drivers for decreasing Selwyn River summer flows. Using the desktop analysis and modelling approaches combined with developing a conceptual model based on existing data and literature has provided insight into the effects of both climatic conditions and abstraction on river flows.

The trend analysis was carried out for the upper and lower Selwyn River flow sites, but also surrounding river flow sites and nearby rainfall stations. Analysing a range of different variables and processing annual, monthly and 7- day ALF trends provided insight into changes in total flows, but also changes in the seasonal distributions of flows. The lack of significant trends found in rainfall, alpine river flows and other lowland stream flows indicates that the decreasing trend in the Selwyn River flow over the summer months is not being driven by a change in water coming into the catchment but rather by either increasing abstraction, increasing evapotranspiration or a combination of these two factors. This aligns with the findings of Mckerchar & Schmidt (2007), who concluded that the change in flow in the lower Selwyn River cannot be explained by climate alone. Therefore, while the trend analyses contained in this thesis included a wider range of sites and variables to Mckerchar & Schmidt (2007), the conclusions were similar.

The findings of this research indicate that the MODFLOW model developed for the Selwyn/Te Waihora Catchment is capable of simulating interactions between surface water and groundwater. The model has been demonstrated to capture the changes in the wetting and drying reaches under several different scenarios. The model results, combined with the trend analysis, provide an improved understanding of the factors influencing the flows in the lower Selwyn River.

The steady state MODFLOW model produced an adequate match with observed groundwater levels and lowland stream flows. This provided confidence in the model's ability to be used to predict magnitude and direction of change in the scenario analysis. Matching the transient response in the changes in river flows required a change to the riverbed conductance, which highlighted that the steady state and transient calibrations may be different. This difference is likely due to the different timings of recharge, inflows to the catchment, abstraction, and the effects of aquifer storage (which is not considered in a steady state model). The steady state and transient models are both useful in providing an understanding of the catchment and the long- and short-term impacts of climate and abstraction.

As the modelling developed in this research was developed using existing data, the data sets for a full model calibration were not available; this results in some uncertainty around the predictions of dry reaches in the mid plains reaches of the Selwyn River. However, the model was able to meet the objective of simulating daily changes in drying and flowing reaches in response to an increased flow event. This initial modelling could be used to inform a field study into the longitudinal flow changes in the Selwyn River, and this modelling could be calibrated further in the future as new data become available.

The combination of trend analysis and numeric modelling indicate that both climate and abstraction are impacting the flow in the Selwyn River. The recharge scenarios run using the steady state model show how wet years and dry years result in differing groundwater levels and stream flows, while the abstraction scenarios showed that increased abstraction resulted in lower flows and increased drying of the river. Combining these findings with the trend analysis leads to the conclusion that as abstraction has increased over recent decades, the flows in the lower Selwyn River have declined; this declining trend is overlaid with the year-to-year climatic conditions (simulated in the recharge scenarios) which result in the more recent dry seasons having lower river flows than similar dry years which occurred earlier. Even without further allocation within the catchment, there is potential that abstractors could increase their usage within their current allocation and this may worsen the low flows and dry reaches from that which is seen currently.

7 References

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Appendix 1: Model layer elevations

This appendix contains maps of the elevation of model cells within each layer. Colours in each map are scaled to the elevations within each layer.

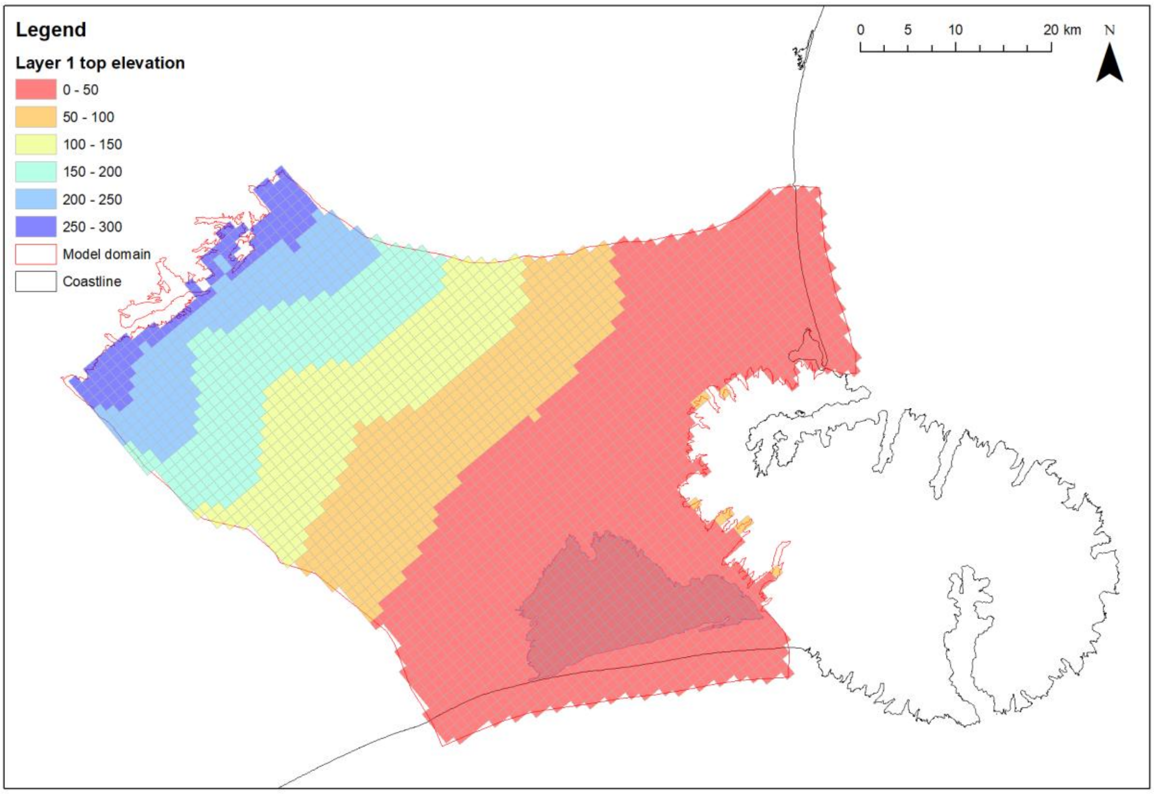

Figure A.1 Elevations of the top of layer 1 in m above sea level.

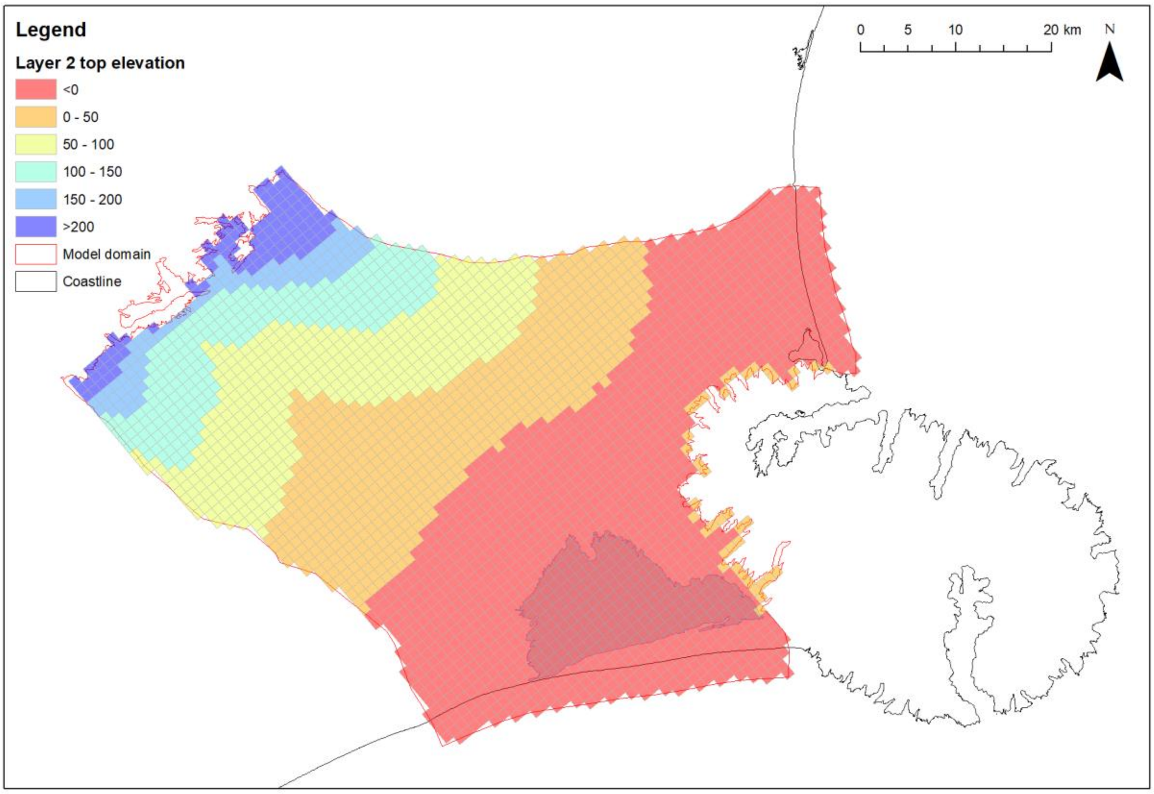

Figure A.2 Elevations of the top of layer 2 in m above sea level.

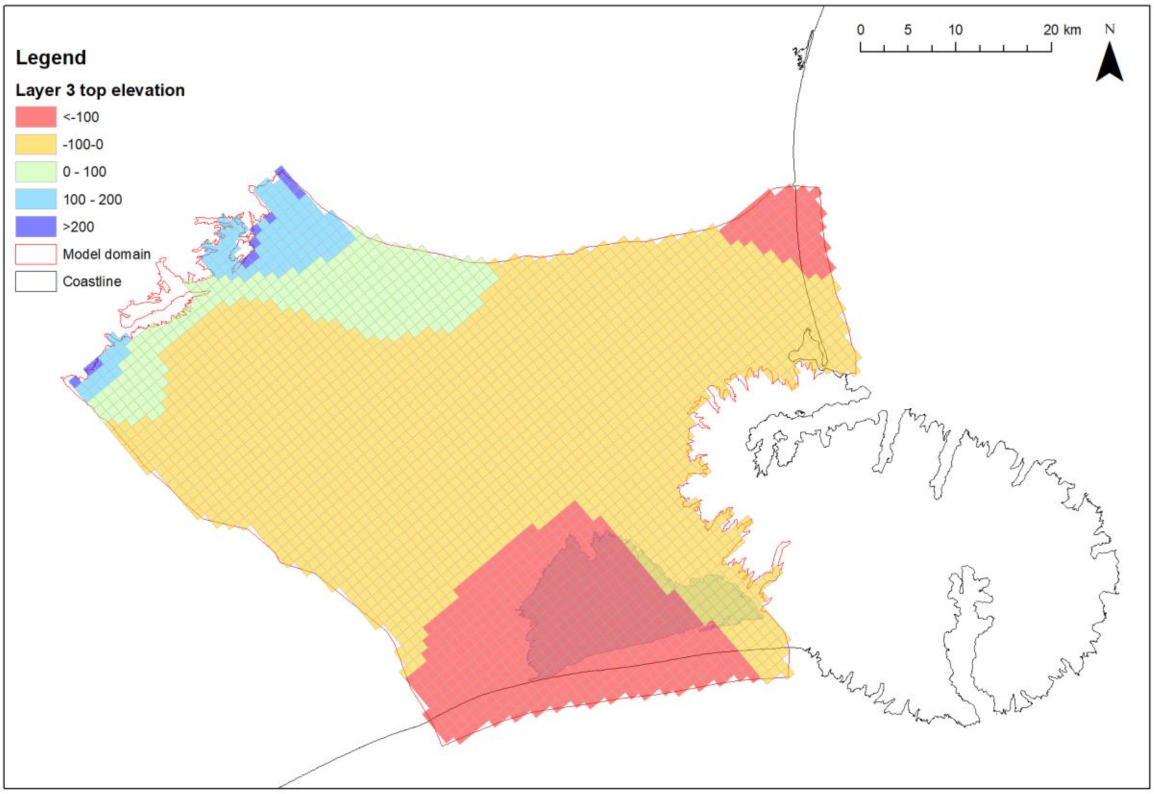

Figure A.3 Elevations of the top of layer 3 in m above sea level.

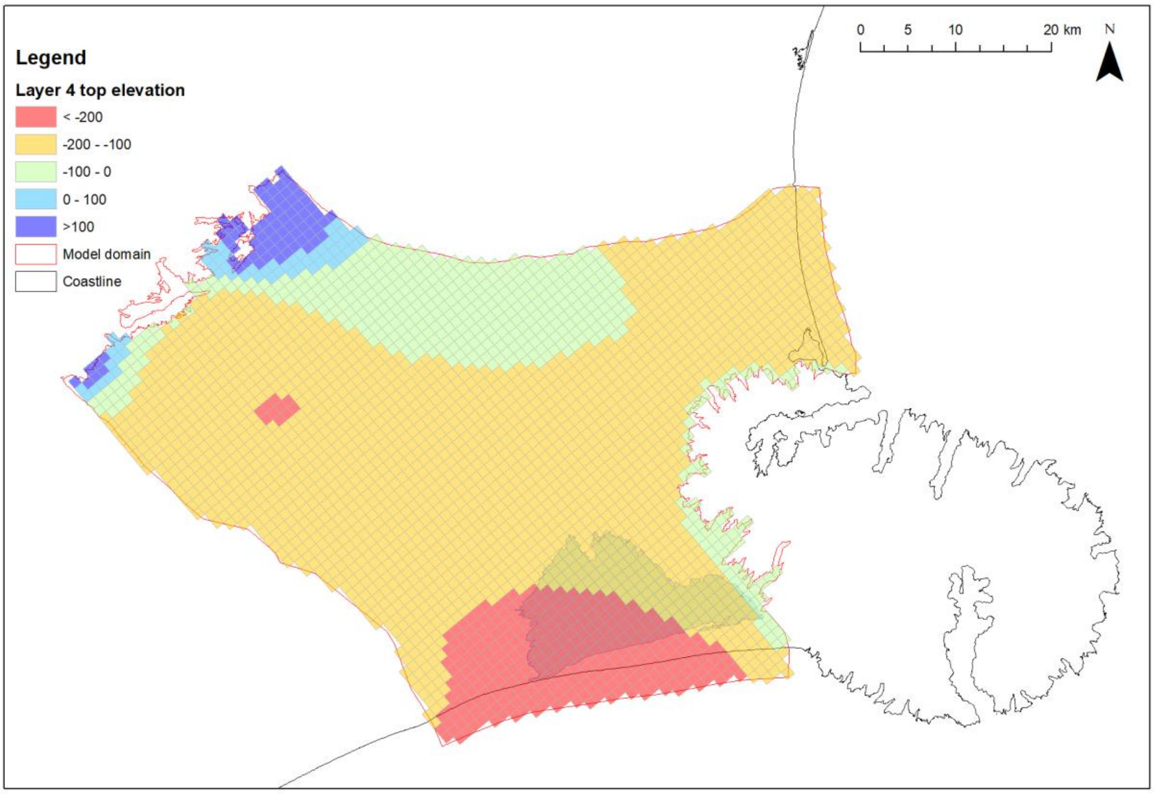

Figure A.4 Elevations of the top of layer 4 in m above sea level.

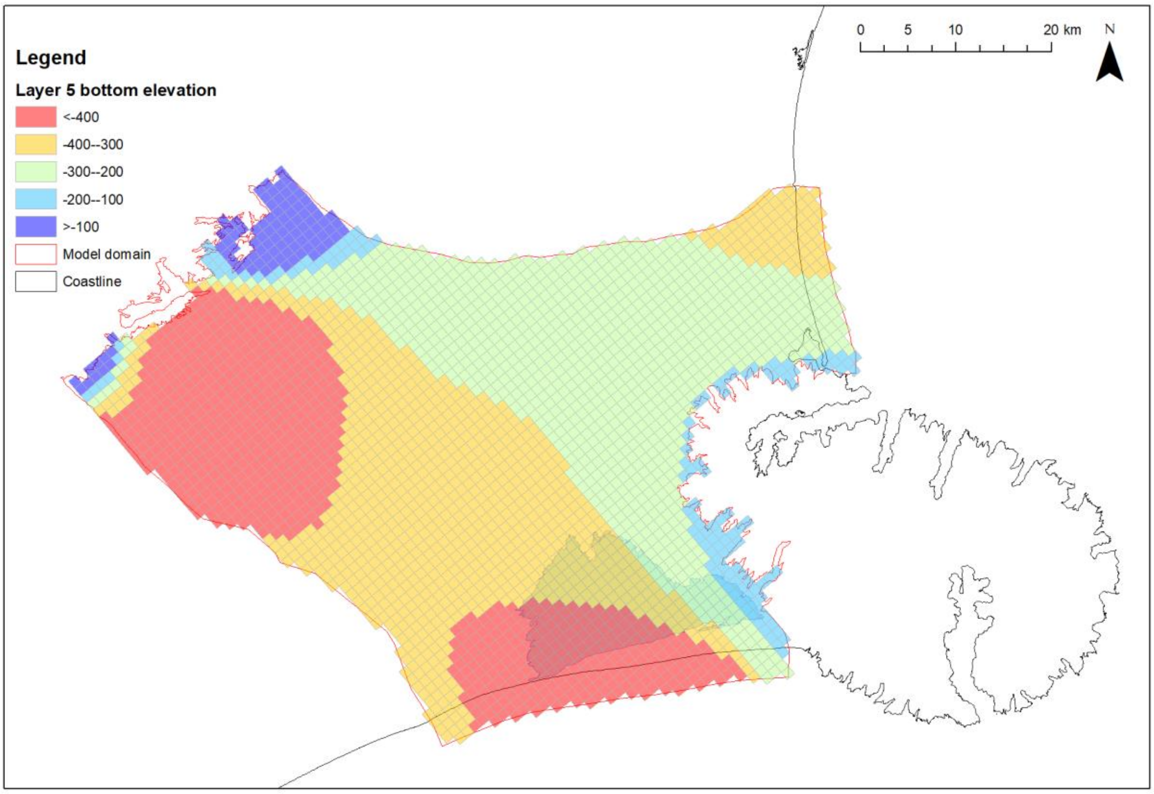

Figure A.5 Elevations of the top of layer 5 in m above sea level.

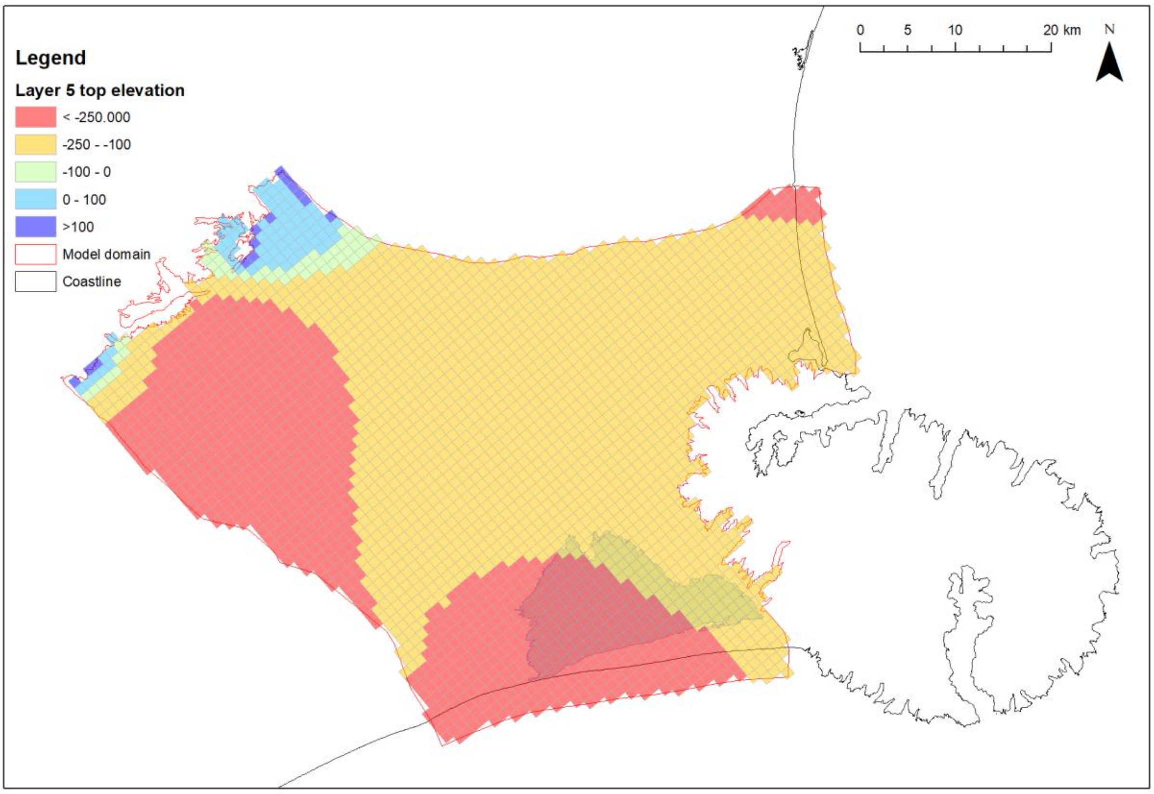

Figure A.6 Elevations of the bottom of layer 5 in m above sea level.

Appendix 2: Steady state parameters

This appendix documents the final steady state parameters used, the calibration range used for autocalibrations and a description of each parameter.

Table A.1 Final steady state parameters

Name	Final parameter value	Minimum calibration value	Maximum calibration value	Units	Description of parameter
RIV_509	0.001	0.001	50	m^2/day	Rakaia River conductivity. Bottom reach
RIV_501	0.004308	0.001	50	m^2/day	Waimakariri River conductivity. Top reach
RIV_505	75	0.001	75	m^2/day	Waimakariri River conductivity. Bottom reach
RIV_504	75	0.001	75	m^2/day	Waimakariri River conductivity. Lower plains
RIV_503	33.842	0.001	50	m^2/day	Waimakariri River conductivity. Mid plains
RIV_502	17.056	0.001	50	m^2/day	Waimakariri River conductivity. Upper plains
RIV_508	0.12683	0.001	50	m^2/day	Rakaia River conductivity. Lower plains
RIV_507	19.956	0.001	50	m^2/day	Rakaia River conductivity. Upper plains
RIV_506	0.002136	0.001	50	m^2/day	Rakaia River conductivity. Top reach
GHB_302	9999	9999	9999	m^2/day	Coastal boundary conductivity. Northern coast
GHB_301	9999	9999	9999	m^2/day	Coastal boundary conductivity. Southern coast
DRN_208	3.3983	0.001	75	m^2/day	Otukaikino River conductance
DRN_210	2.627682	0.001	75	m^2/day	Heathcote River conductance
DRN_203	8.7763	0.001	75	m^2/day	Harts Creek conductance
DRN_209	0.447755	0.001	75	m^2/day	Avon River conductance
DRN_211	1.203495	0.001	75	m^2/day	Styx River conductance
DRN_207	0.001	0.001	75	m^2/day	Waikekewai Creek conductance
DRN_205	0.674	0.001	75	m^2/day	Doyleston Drain conductance
DRN_201	0.79986	0.001	75	m^2/day	Boggy Creek conductance
DRN_216	12.588	0.001	75	m^2/day	L-II River conductance
DRN_204	0.91163	0.001	75	m^2/day	Hanmer Rd Drain conductance
DRN_215	0.93943	0.001	75	m^2/day	Halswell River conductance
DRN_212	8.2877	0.001	75	m^2/day	Lee River conductance
DRN_213	0.001	0.001	75	m^2/day	Jollies Brook conductance
DRN_214	0.001	0.001	75	m^2/day	Tentburn River conductance

HK_101	Pilot points (0.005-995)	1.00E-10	1000	m/day	Layer 1 Horizontal hydraulic conductivity
HK_102	Pilot points (6.5-498)	1.00E-10	500	m/day	Layer 2 Horizontal hydraulic conductivity
HK_103	Pilot points (0.0002-7.4)	1.00E-10	100	m/day	Layer 3 Horizontal hydraulic conductivity
HK_104	Pilot points (0.007-0.497)	1.00E-10	100	m/day	Layer 4 Horizontal hydraulic conductivity
HK_105	Pilot points (3.5E-7 – 5.04E-7)	1.00E-10	100	m/day	Layer 5 Horizontal hydraulic conductivity
VK_2001	100	3	100	-	Layer 1 Vertical anisotropy
GHB_401	0.000123	0.0001	0.0004	m^2/day	Te Waihora conductance
VK_2002	100	3	100	-	Layer 2 Vertical anisotropy
VK_2003	4.4261	3	100	-	Layer 3 Vertical anisotropy
VK_2004	6.0877	3	100	-	Layer 4 Vertical anisotropy
VK_2005	9.6853	3	100	-	Layer 5 Vertical anisotropy
SFR_11101	0.1	1.00E-10	100	m^2/day	Hororata River conductance
SFR_11104	0.18091	1.00E-10	100	m^2/day	Upper Selwyn River conductance
SFR_11103	0.5	1.00E-10	100	m^2/day	Waianiwaniwa River conductance
SFR_11102	0.2	1.00E-10	100	m^2/day	Hawkins River conductance
SFR_11105	0.001065	1.00E-10	100	m^2/day	Upper plains Selwyn River conductance
SFR_11108	1.5	1.00E-10	100	m^2/day	Irwell River conductance
SFR_11106	0.25352	1.00E-10	100	m^2/day	Lower plains Selwyn River conductance
SFR_11107	0.2	1.00E-10	100	m^2/day	Lower Selwyn River conductance

Appendix 3: Monthly trend analysis results

Table A.2 P value for trend analysis of monthly mean flows

Site	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Selwyn River at Whitecliffs (1984-2019)	0.653	0.673	0.824	0.289	0.647	0.114	0.592	0.539	0.247	0.881	0.307	0.205
Selwyn River at Whitecliffs (full record)	0.433	0.369	0.838	0.761	0.28	0.587	0.577	0.757	0.333	0.708	0.441	0.52
Selwyn River at Coes Ford	0.037	0.016	0.002	0.035	0.214	0.906	0.824	0.784	0.102	0.522	0.187	0.048
Waimakariri River at Old Highway Bridge	0.908	0.917	0.052	0.276	0.823	0.107	0.042	0.856	0.465	0.317	0.17	0.289
Halswell River at Ryan's Bridge	0.797	0.333	0.322	0.528	0.469	0.168	0.414	0.761	0.388	1	0.498	0.304
Doyleston Drain at The Lake Rd	0.545	1	0.656	0.495	0.39	0.744	1	0.813	0.678	0.938	0.657	0.722
Harts Creek at Timberyard Point	1	0.502	0.36	0.76	0.36	0.584	0.661	0.189	0.511	0.324	0.913	0.827
Avon River at Gloucester St	0.46	0.443	0.67	0.691	0.989	0.653	0.41	0.967	0.964	0.881	0.522	0.225
Heathcote River at Buxton Terrace	0.748	0.666	0.617	0.412	1	0.521	0.775	0.915	0.412	0.475	0.392	0.335
Rakaia River at Fighting Hill	0.082	0.375	0.038	0.296	0.661	0.745	0.328	0.795	0.678	0.196	0.762	0.154

Table A.3 Sen slope for trend analysis of monthly mean flows

Site	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Selwyn River at Whitecliffs (1984-2019)	0.005	-0.003	-0.003	0.017	0.012	0.041	-0.021	-0.023	-0.044	-0.006	-0.024	-0.022
Selwyn River at Whitecliffs (full record)	-0.005	-0.005	-0.002	-0.004	-0.011	0.008	0.009	-0.005	-0.015	-0.005	-0.009	-0.005
Selwyn River at Coes Ford	-0.016	-0.018	-0.024	-0.018	-0.012	0.002	-0.005	-0.01	-0.06	-0.012	-0.016	-0.019
Waimakariri River at Old Highway Bridge	0.023	0.026	-0.463	-0.374	0.138	0.742	0.567	0.068	-0.375	-0.526	-0.541	-0.476
Halswell River at Ryan's Bridge	0.001	0.005	0.001	0.003	0.005	0.012	0.009	0.005	0.01	0	0.005	0.005
Doyleston Drain at The Lake Rd	0	0	0	0	-0.001	-0.001	0	0.001	-0.001	-0.001	0.001	0
Harts Creek at Timberyard Point	0.002	-0.017	-0.02	-0.009	-0.033	-0.019	-0.008	-0.042	-0.023	-0.011	-0.002	-0.006
Avon River at Gloucester St	-0.003	-0.002	-0.002	-0.001	0	0.003	-0.004	0	0	0.001	-0.003	-0.005
Heathcote River at Buxton Terrace	0.001	0.001	0.002	0.004	0	0.006	0.002	-0.001	0.004	0.004	0.003	0.003
Rakaia River at Fighting Hill	-1.682	-0.594	-1.29	-0.594	0.362	0.218	0.534	-0.138	0.34	-1.328	-0.394	-2.023

Table A.4 P value for trend analysis of monthly rainfall totals

Site	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Selwyn River at Whitecliffs	0.527	0.456	0.709	0.206	0.256	0.183	0.221	0.816	0.598	0.198	0.495	0.299
13 Mile Bush	0.416	0.982	0.799	0.794	0.46	0.536	0.596	0.303	0.977	0.622	0.445	0.871
High Peak	0.361	0.48	0.903	0.198	0.119	0.635	0.585	0.669	0.448	0.526	0.896	0.485
Ridgens Rd	0.129	0.074	0.972	0.475	0.432	0.529	0.163	0.475	0.247	0.043	0.269	0.695
Halswell River at Ryan's Bridge	0.747	0.32	0.535	0.568	0.944	0.224	0.327	0.455	0.528	0.387	0.747	0.321
Taumutu	0.855	0.246	0.668	0.139	0.274	0.546	1	0.324	0.474	0.511	0.139	0.155

Table A.5 Sen slope for trend analysis of monthly rainfall totals

Site	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Selwyn River at Whitecliffs	-0.638	-0.5	0.204	1.177	-0.766	1.126	-0.952	-0.144	-0.424	1.152	-0.625	0.65
13 Mile Bush	-0.248	0.01	-0.077	-0.157	-0.155	0.242	-0.23	-0.389	0.022	0.159	-0.352	0.08
High Peak	-0.28	-0.187	0.033	-0.422	-0.513	0.171	-0.169	-0.129	0.191	0.24	0.028	0.2
Ridgens Rd	-0.857	-0.95	0	0.688	-0.455	0.444	-1	-0.5	-0.5	1.119	-0.741	0.167
Halswell River at Ryan's Bridge	-0.339	-0.541	0.314	0.833	0.252	1.017	-1	-0.716	0.372	-0.764	-0.243	0.464
Taumutu	0.375	-1.632	0.351	3.252	-2.062	1.438	0	-1.858	0.35	-2.001	2.375	-1.599

Appendix 4: Steady state scenario flow maps

This appendix contains maps of flow in the SFR2 cells for each scenario. All maps use the same colour scheme, focused on showing changes in reaches which were simulated to be dry or having low flows (<1 m^3/s).

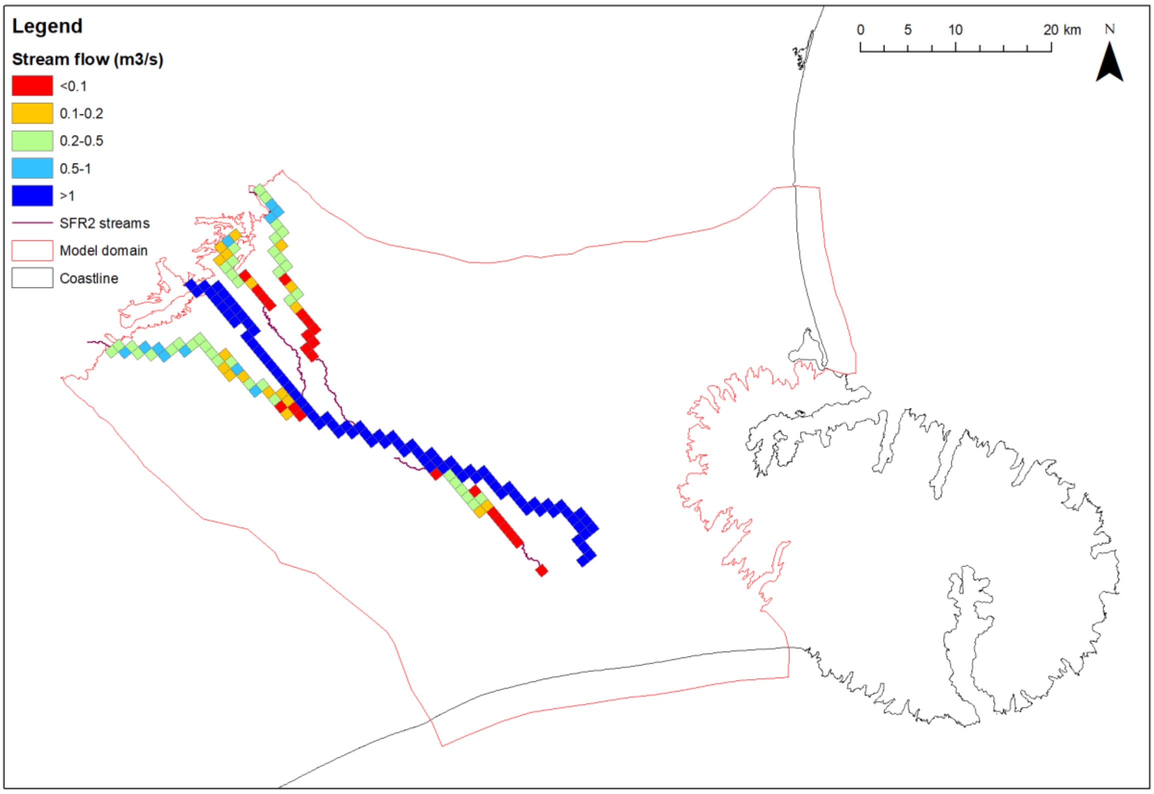

Figure A.7 Baseline scenario stream flow map

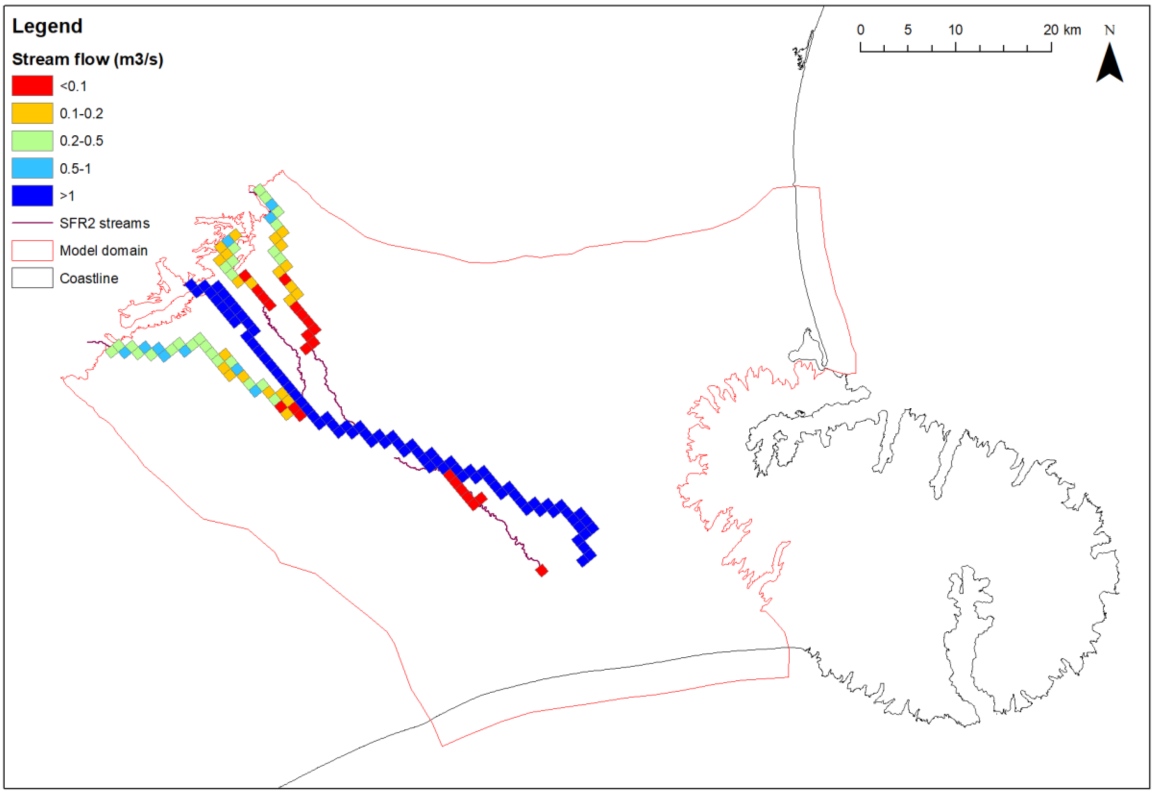

Figure A.8 No water race recharge scenario stream flow map.

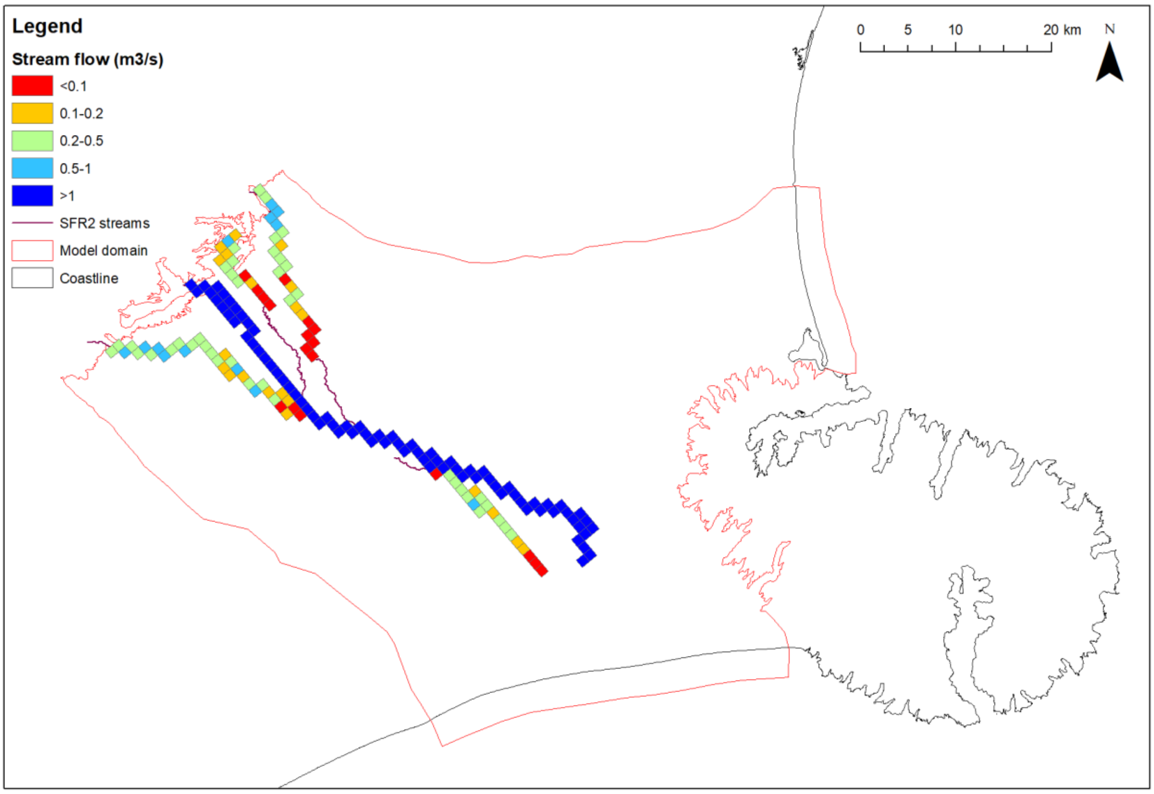

Figure A.9 Increased recharge scenario stream flow map.

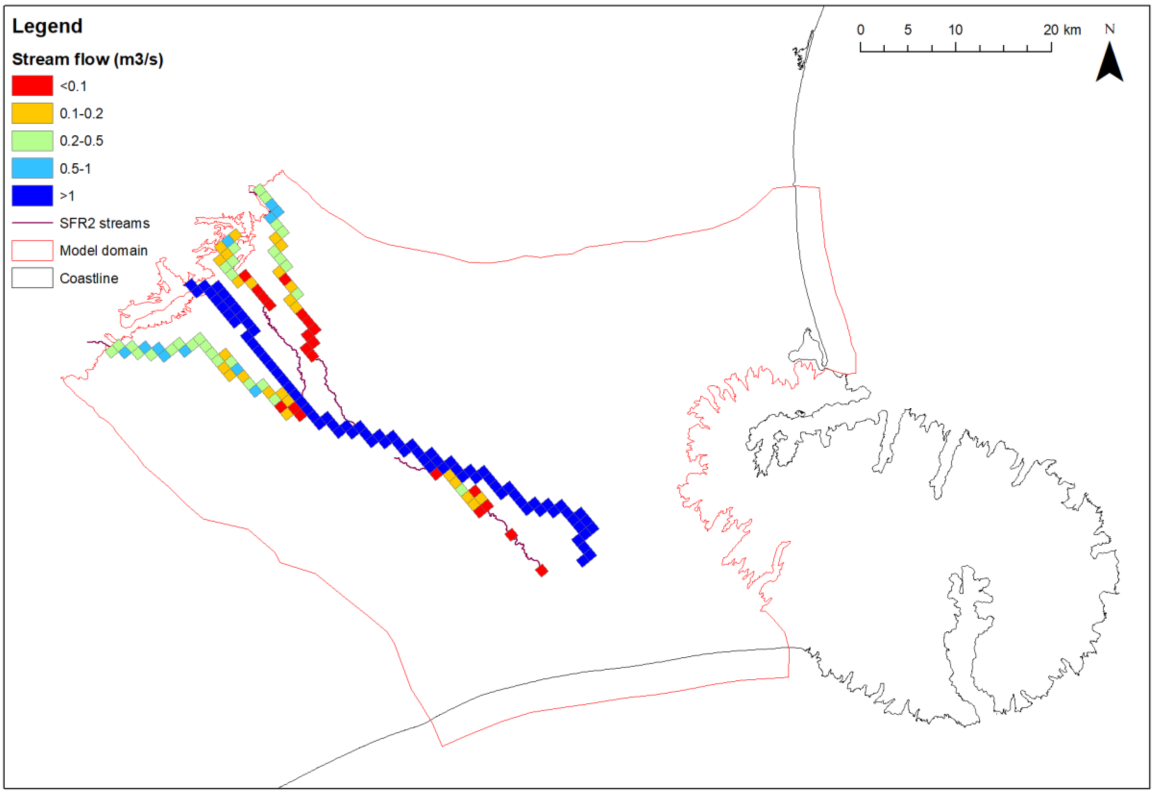

Figure A.10 Decreased recharge scenario stream flow map.

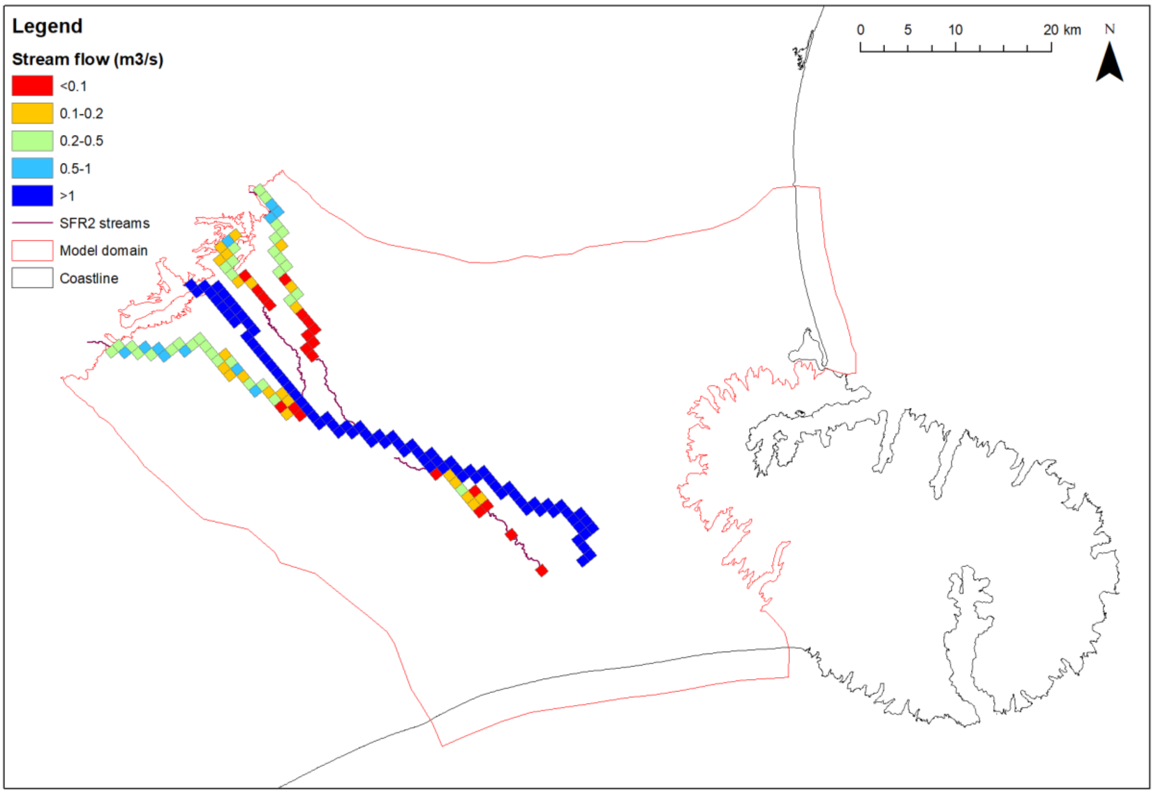

Figure A.11 Increased abstraction scenario stream flow map.

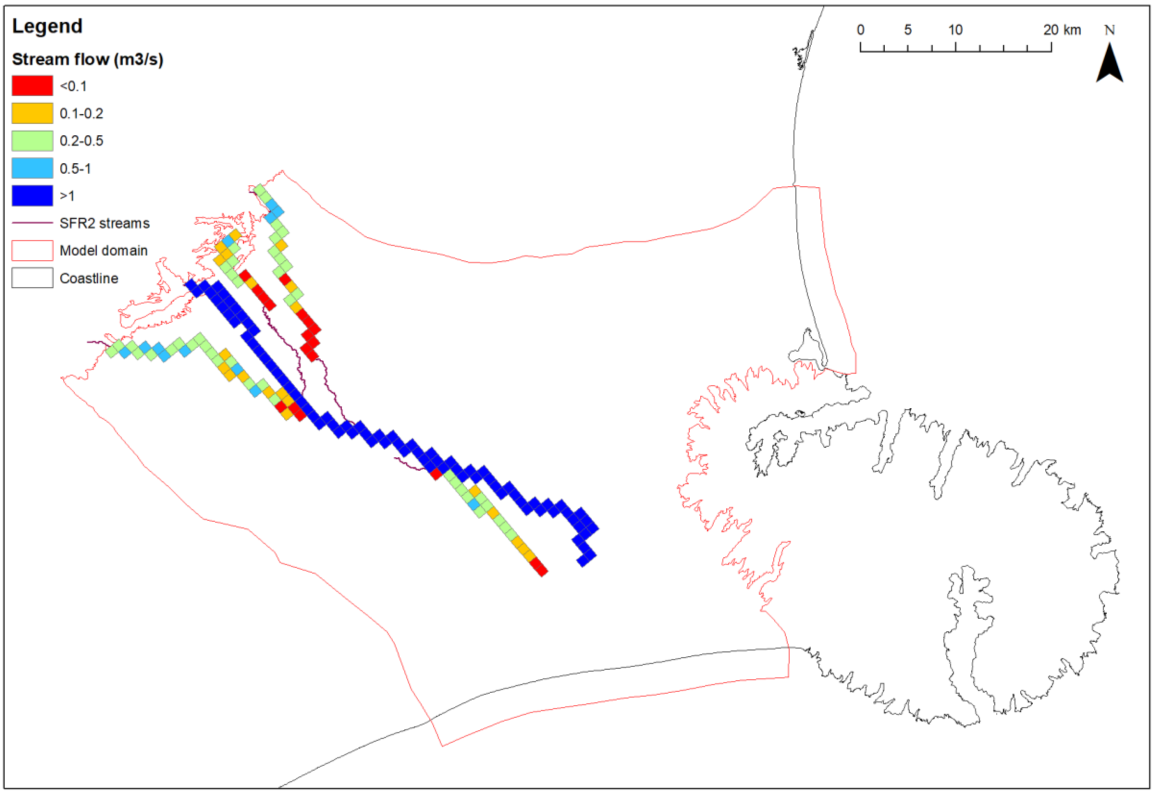

Figure A.12 Decreased abstraction scenario stream flow map.

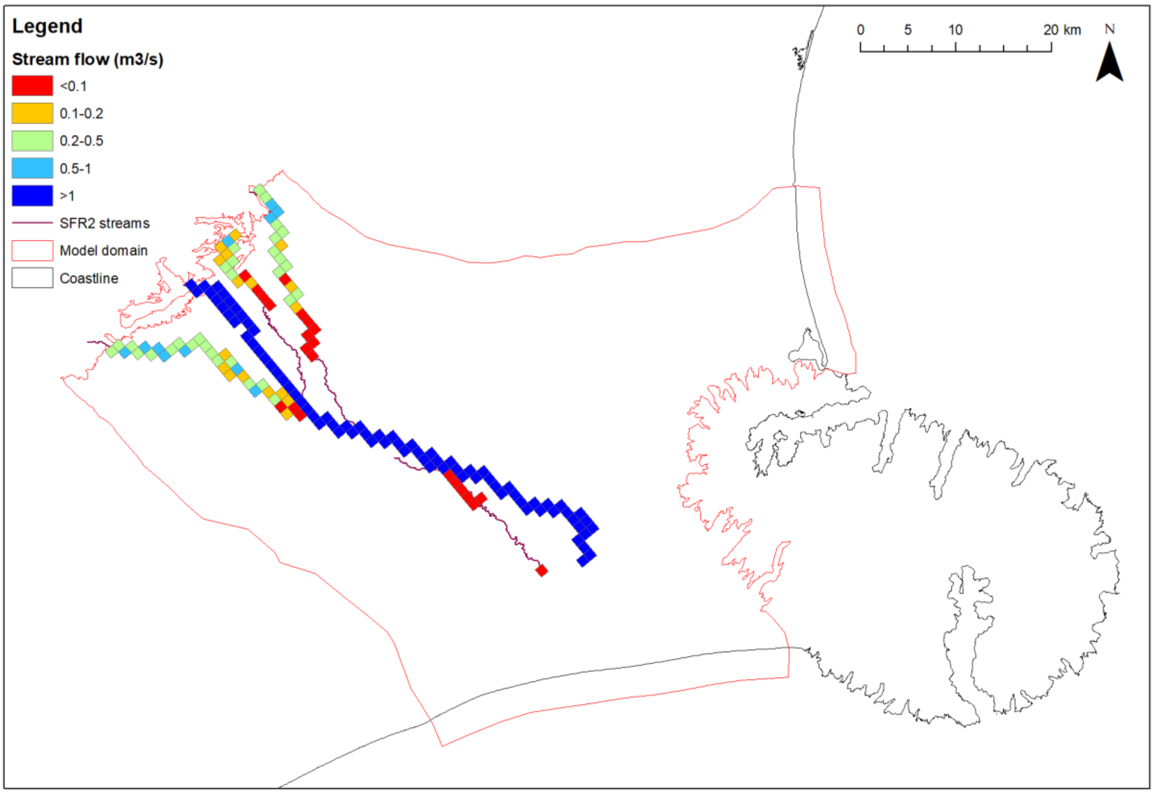

Figure A.13 25% Increase in Abstraction scenario stream flow map.

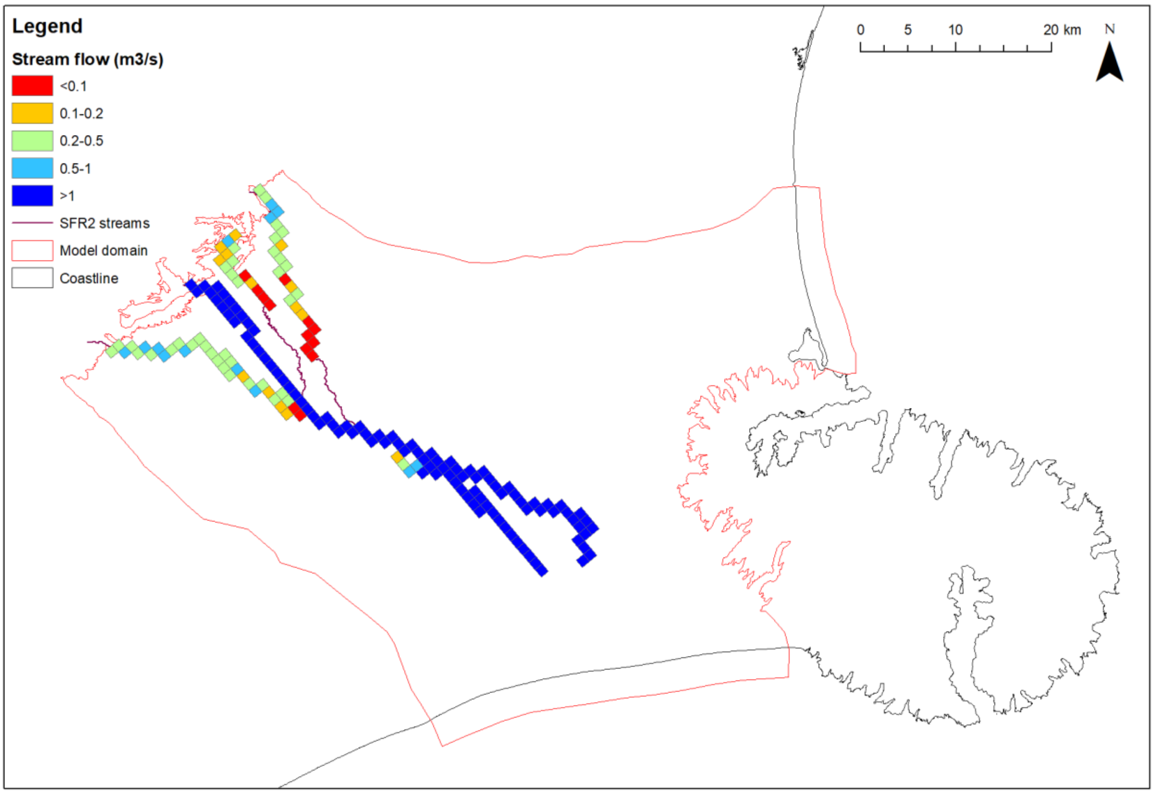

Figure A.14 No abstraction scenario stream flow map.

Appendix 5: Transient stream flows

This appendix contains maps of surface flow in SFR2 cells simulated for the period 23/2/2019 to 1/3/2019. This shows a period where the Selwyn River has a dry middle reach and hill fed rainfall event causes the river to flow for its full length before becoming disconnected again.

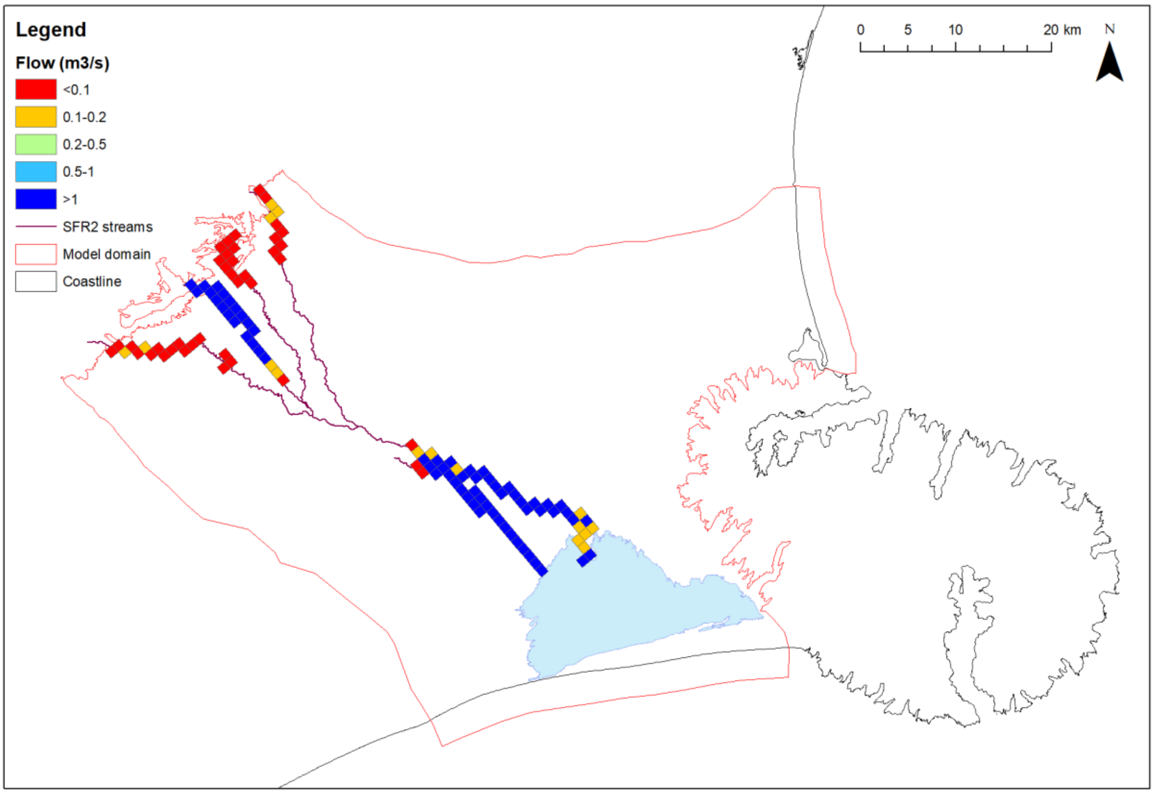

Figure A.15 Surface flow in SFR2 cells on 23/2/2019

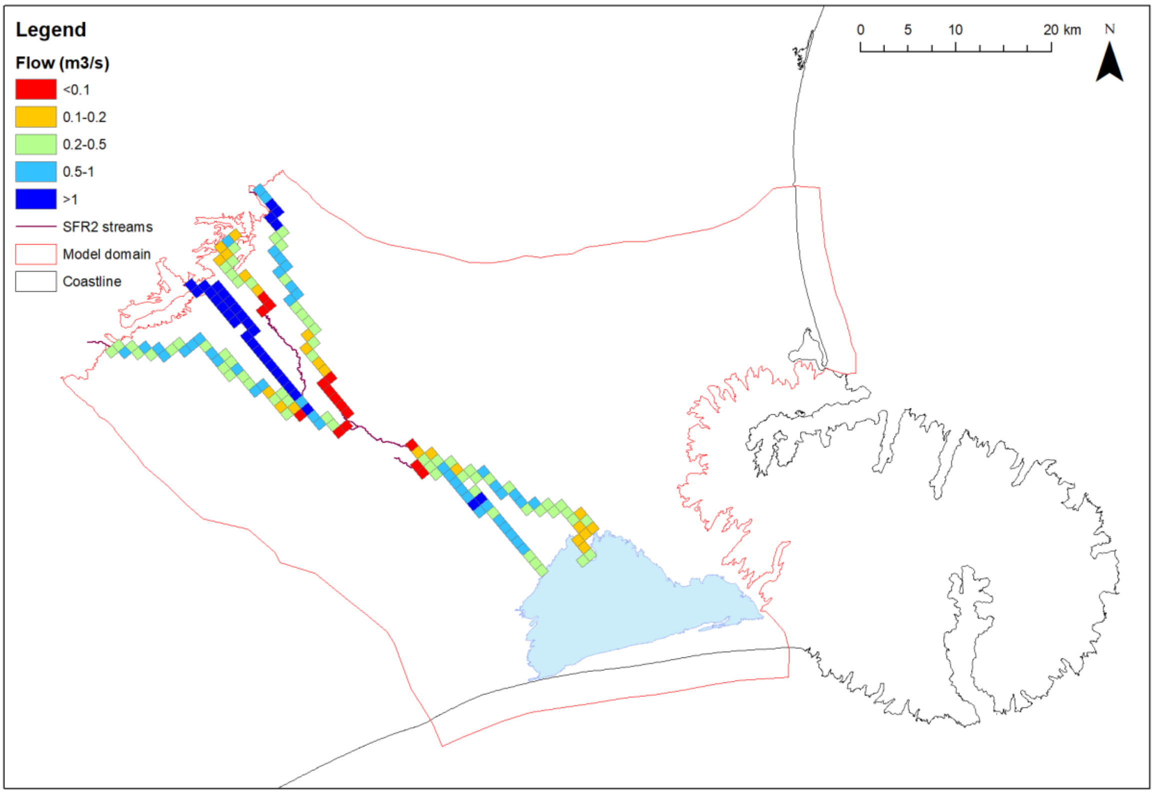

Figure A.16 Surface flow in SFR2 cells on 24/2/2019

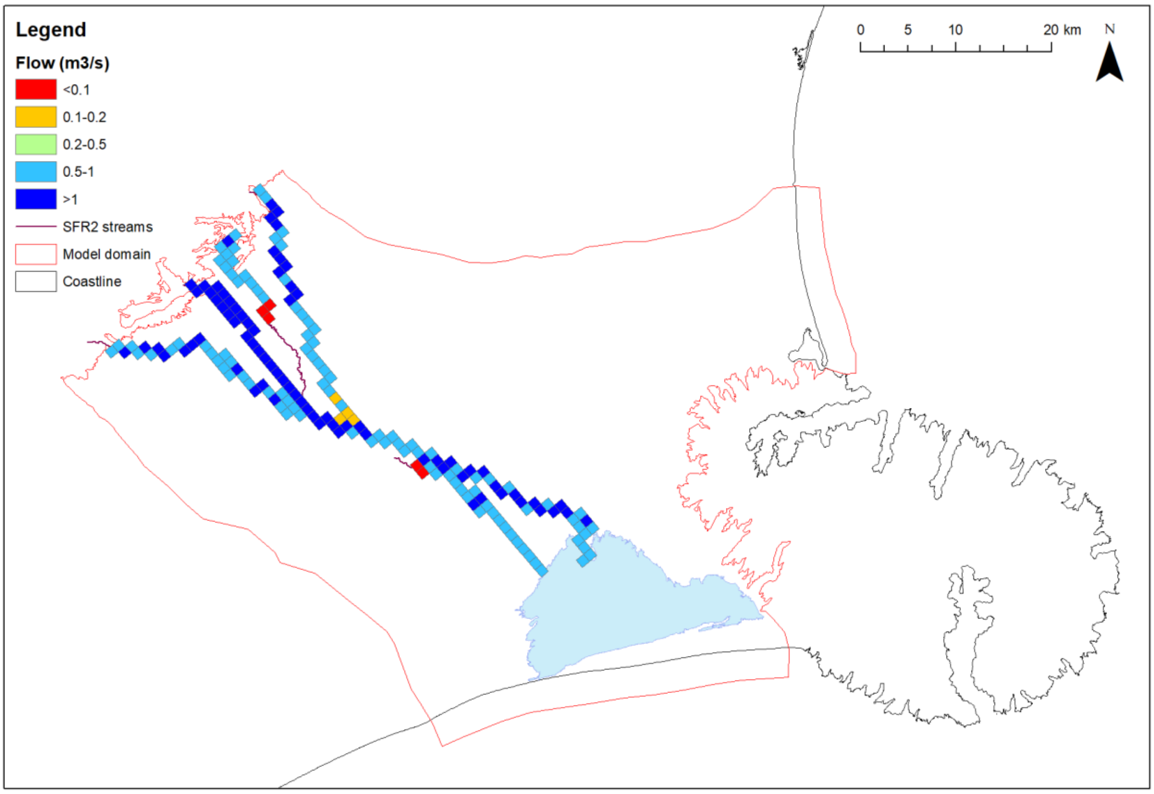

Figure A.17 Surface flow in SFR2 cells on 25/2/2019

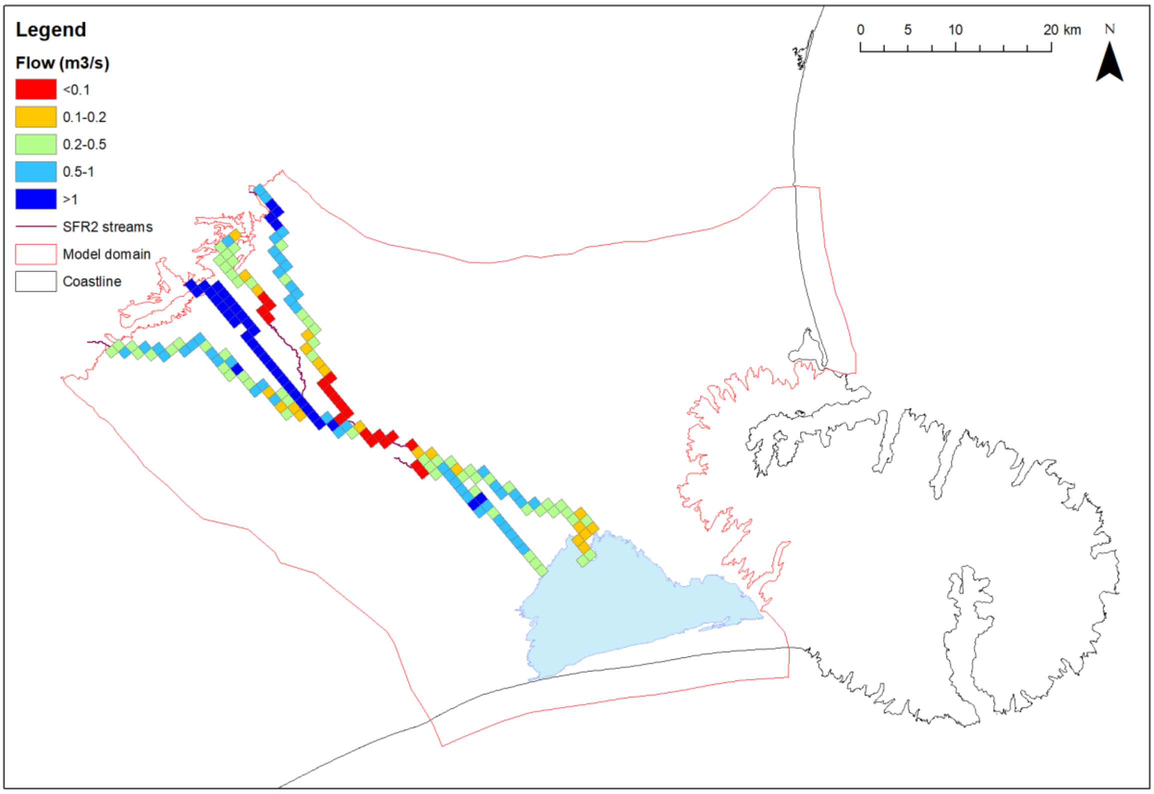

Figure A.18 Surface flow in SFR2 cells on 26/2/2019

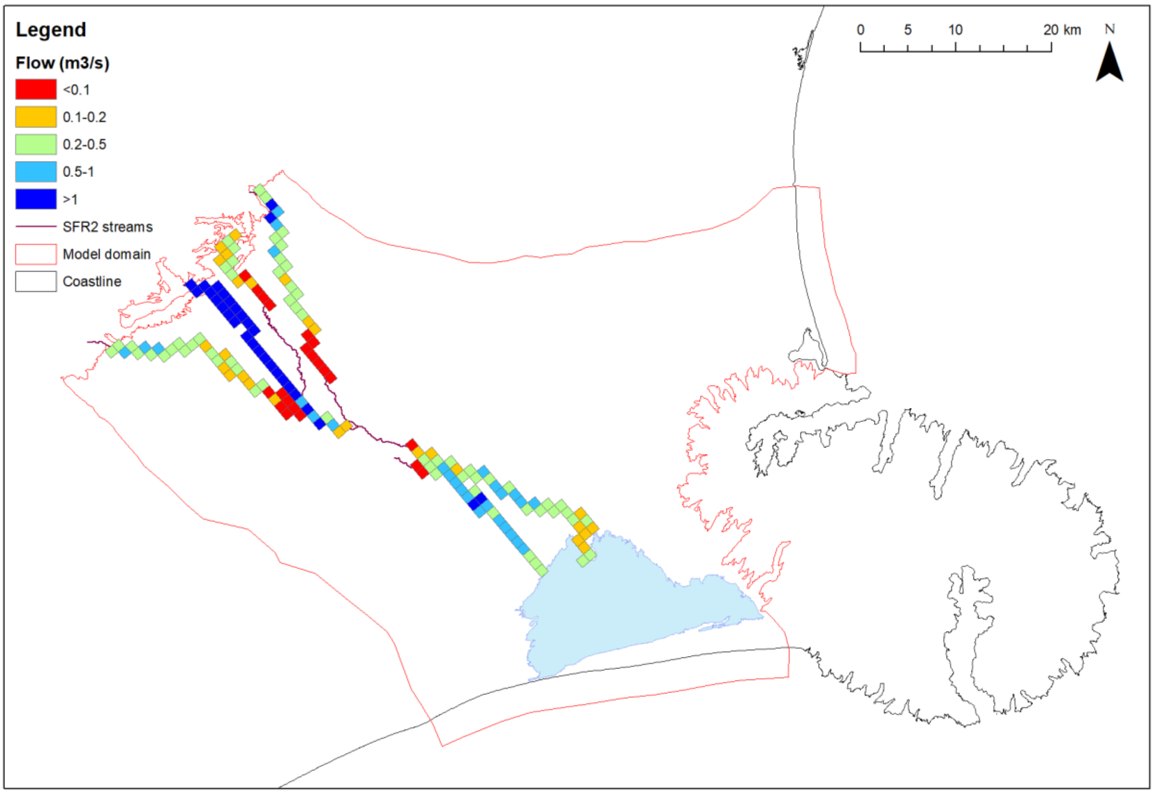

Figure A.19 Surface flow in SFR2 cells on 27/2/2019

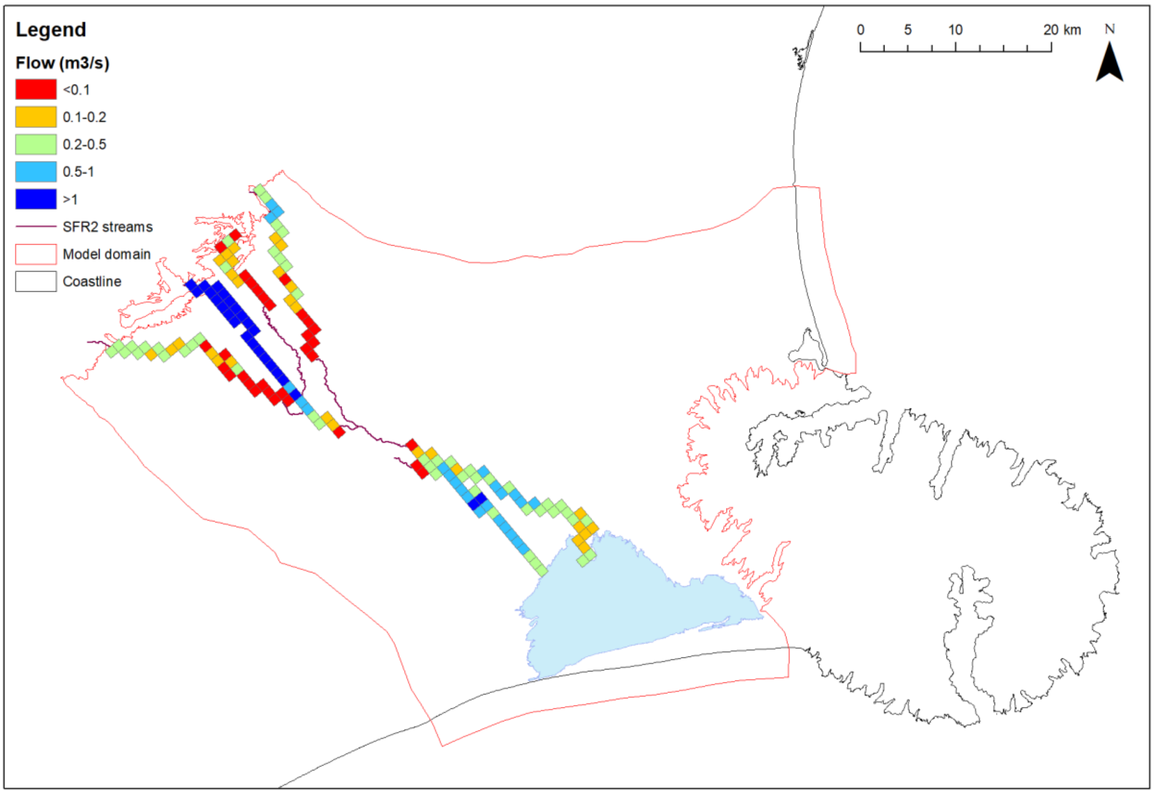

Figure A.20 Surface flow in SFR2 cells on 28/2/2019

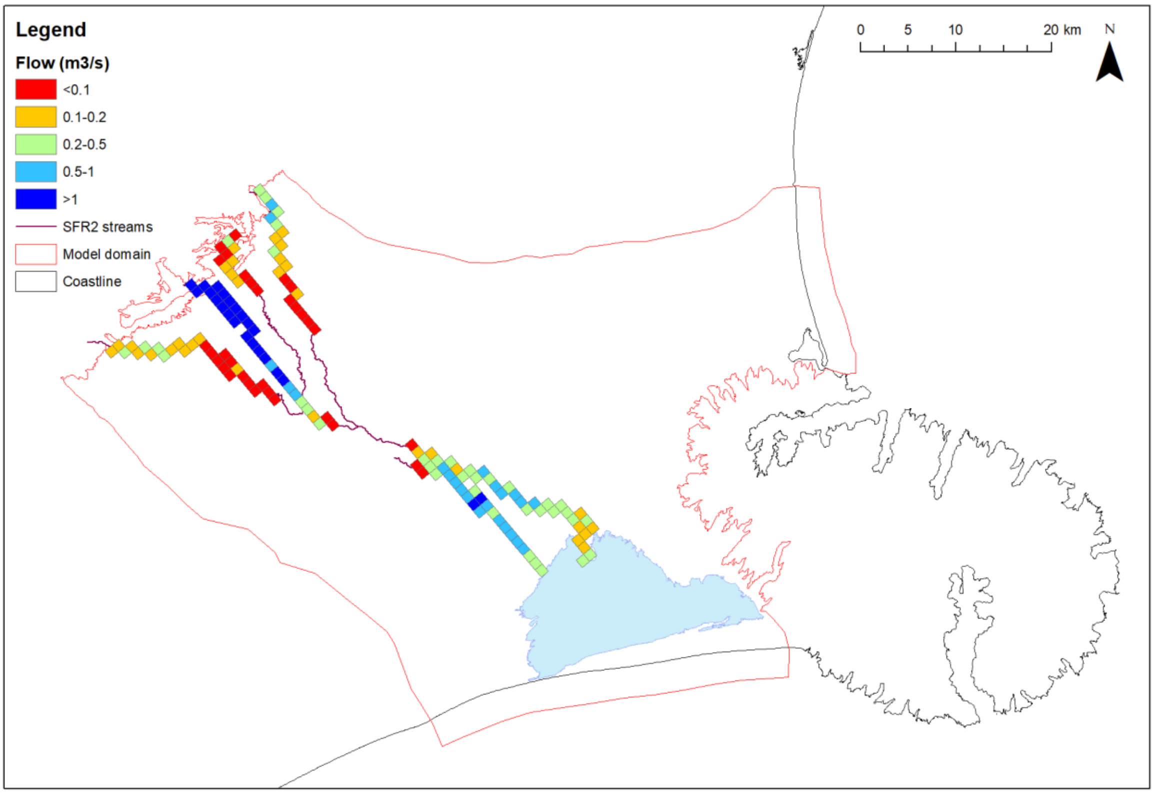

Figure A.21 Surface flow in SFR2 cells on 1/3/2019